IRENA
International Renewable Energy Agency

Sustainable bioenergy potential

in Caribbean small island developing states

ISBN: 978-92-9260-576-6

Citation: IRENA (2024), *Sustainable bioenergy potential in Caribbean small island developing states*, International Renewable Energy Agency, Abu Dhabi.

About IRENA

The International Renewable Energy Agency (IRENA) serves as the principal platform for international co-operation, a centre of excellence, a repository of policy, technology, resource and financial knowledge, and a driver of action on the ground to advance the transformation of the global energy system. An intergovernmental organisation established in 2011, IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity.

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Acknowledgements

This report was developed under the guidance of Roland Roesch (Director, IRENA Innovation and Technology Center) and Ricardo Gorini. It was authored by Luiz A. Horta Nogueira, Eric A. Ocampo Batlle (Consultants) and Walter J. Sanchez (ex-IRENA); and Athir Nouicer and Chun Sheng Goh (IRENA). The report benefited from the reviews and inputs from IRENA staff: Arieta Gonelevu Rakai and Paul Komor. The report also benefited from valuable reviews and contributions from external experts: Ana Maria Majano (LEDS LAC), Seungwoo Kang (Total Energies). IRENA would like to thank the Government of Denmark for supporting IRENA with the work that formed the basis of this report.

Editorial and production support were provided by Francis Field and Stephanie Clarke, with design by Phoenix Design Aid. The report was edited by Fayre Makeig.

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ABBREVIATIONS

C0	business as usual scenario
C1	business as usual with improved sugarcane yield scenario
C2	new framework – without irrigation scenario
C3	new framework – with irrigation scenario
CEPCI	Chemical Engineering Plant Cost Index
CO_2	carbon dioxide
tCO_2eq	tonnes of carbon dioxide equivalent
CPO	crude palm oil
CPKO	crude palm kernel oil
CV	calorific value
EFB	empty fruit bunch (from oil palm)
EIA	US Energy Information Administration
FAO	Food and Agriculture Organization
FFB	fresh fruit bunch (from oil palm)
GDP	gross domestic product
GHG	greenhouse gas
HV	heating value
HHV	higher heating value
LFG	landfill gas
LHV	lower heating value
MSW	municipal solid waste
PKS	palm kernel shell
POM	palm oil mill
POME	palm oil mill effluent
SDG	Sustainable Development Goal
SIDS	small island developing states
WtE	waste to energy

UNITS OF MEASURE

GW	gigawatt
GWh	gigawatt hour
ha	hectare
kg	kilogramme
kg/c/d	kilogrammes/capita/day
kha	kilohectare
km^2	square kilometre
kt	kilotonne
kWh	kilowatt hour
m^3	cubic metre
Mha	million hectare
MJ	megajoule
Mt	million tonne
MW	megawatt
MWh	megawatt hour

EXECUTIVE SUMMARY

To explore all possible options for sustainable bioenergy development in various regions, IRENA has conducted a series of studies focusing on different feedstocks, ranging from energy crops to agricultural residues. Each study provides fact-based solutions suited to different regional contexts, with sustainability being the primary consideration to ensure bioenergy development aligns with ecological functions and socio-economic goals. Decision makers must be particularly mindful of the limitations within the estimates provided, as further analysis considering local ecological and socio-economic contexts is required to strike a balance between maximising productivity and preserving ecological conservation efforts.

This report provides a preliminary assessment of the bioenergy potential of six small island developing states (SIDS) in the Caribbean: Cuba, the Dominican Republic, Haiti, Jamaica, Trinidad and Tobago, and Guyana. These countries comprise about 94% of the region's area and 93% of its population.

Three raw materials for the production of liquid biofuels (ethanol and biodiesel), and bioelectricity were considered:

- sugarcane, a well-known, high-yield crop developed across the region since the colonial period;
- oil palm, prevalent in only Cuba and the Dominican Republic; and
- municipal solid waste in all six countries.

Across the six countries assessed, the land area that could be devoted to sustainable bioenergy crop production (considering legal restrictions and environmental guidelines) was estimated at 2.15 million hectares in 2019. Most of this was in three countries – Cuba (68.7%), the Dominican Republic (12.8%) and Haiti (12%) – and represents a fraction of each country's land area (14.2% in Cuba, 5.7% in the Dominican Republic and 9.3% in Haiti). For the evaluation of bioenergy production potential in the countries considered in this study, just a share of this potential land was adopted.

The potential annual production of sugarcane and oil palm – as well as their conversion into biofuels (ethanol and biodiesel) and bioelectricity – was evaluated assuming average yields in four technological scenarios, in addition to land use. For ethanol, considering the current availability of molasses (distilleries attached to mills), total ethanol production in the islands studied was estimated at 303 million litres, of which Cuba contributes 67.4% and the Dominican Republic 19.4%. When considering an expansion of sugarcane-cultivated areas and a state-of-the-art conversion process in an improved scenario (autonomous distilleries, improved sugarcane production), total potential ethanol production increases to 13.9 billion litres, of which 64.9% is from Cuba and 16.5% from Haiti. Biodiesel from palm oil was estimated at between 843 and 1 386 million litres; however, it is important to note that such preliminary estimates have uncertainties linked to water limitations and soil quality, among other factors, which could result in considerable reductions in the potentials estimated in this report. These levels of biofuel production, with the exceptions of Trinidad and Tobago and Jamaica, largely exceed the domestic demand for fossil fuel in the countries considered.

Bioelectricity generation was evaluated considering cogeneration schemes, in the case of sugarcane and oil palm, and the use of municipal solid waste (MSW) as a source of biomass for biopower generation. Thermal plants burning sugarcane bagasse and straw, along with the use of palm oil's solid residue and biogas from the anaerobic treatment of the liquid waste of palm oil extraction, can generate about 20.6 terawatt hours (TWh) and 2.4 TWh of power, much of it in Cuba and the Dominican Republic. The availability of MSW depends on population density as well as factors such as waste composition and collection processes. In this study, it was estimated that biogas from the anaerobic conversion of MSW in sanitary landfills and the direct burning of fuel from MSW could generate 791 and 1 860 gigawatt hours (GWh) of electricity a year, respectively.

Deploying modern, sustainable systems for the generation and utilisation of biofuel (and biopower) in selected SIDS could mitigate greenhouse gas emissions while offering significant socio-economic benefits, including:

a. A reduction in emissions ranging from 0.71 to 25.7 million tonnes of carbon dioxide equivalent ($MtCO_2eq$) per year, about 56% of which is due to sugarcane-based bioethanol.

b. The creation of between 5 000 and 306 000 jobs.

c. Competitive liquid biofuel costs ranging from USD 0.43 to USD 0.41 per litre for ethanol and USD 0.50 to USD 0.45 per litre for biodiesel.

To realise the total capacity estimated in the higher potential scenario proposed for developing biofuels production systems in SIDS countries over a 10-year period, an annual investment equivalent to about 3% of the Gross Capital Formation observed in those countries is needed.

1. INTRODUCTION

IRENA's comprehensive approach to sustainable bioenergy development involves a series of studies that delve into diverse feedstock options across various regions. These studies meticulously analyse a spectrum of sources, ranging from dedicated energy crops to agricultural residues. The aim is to offer a nuanced understanding of bioenergy development possibilities tailored to specific regional contexts (especially in different continents) and also end-uses (*e.g.* biomass power and biojet fuels) (IRENA, 2018, 2019a, 2019b, 2019c, 2021, 2022a, 2022b).

Notably, the studies are rooted in scientific analysis based on factual data and evidence. By examining different feedstock types, these studies provide a multifaceted view of potential bioenergy sources, considering their availability, feasibility, and impact on the environment. Especially, the emphasis on sustainability within these studies is paramount. A recent report has been released with a comprehensive analysis and discussion on the sustainability aspects of bioenergy (IRENA, 2022c). The focus is on ensuring that bioenergy development aligns with both ecological functions and socio-economic goals while contributing to the climate targets. These findings are intended to empower decision makers with the necessary information to pursue bioenergy development strategies in diverse regions worldwide.

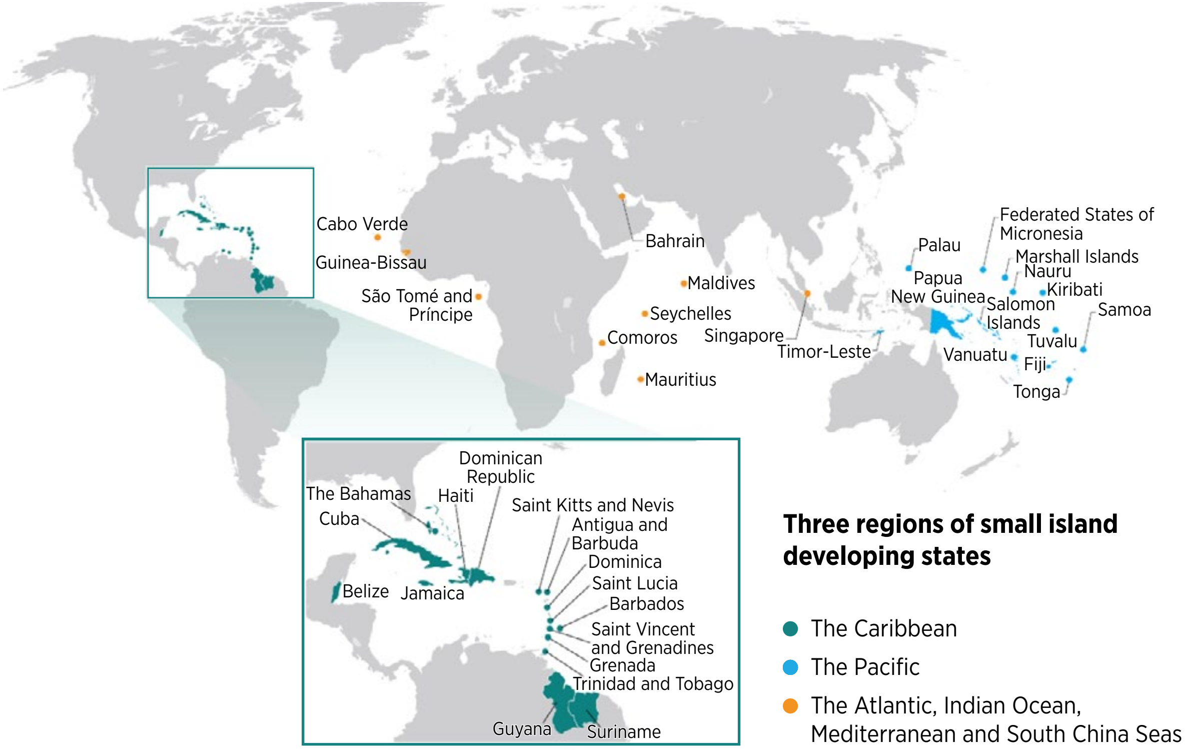
This particular report provides a preliminary assessment of the bioenergy technical potential of six Caribbean Small Island Developing States (Caribbean SIDS): Cuba, Dominican Republic, Haiti, Jamaica, Trinidad and Tobago, and Guyana. These countries correspond to about 94% of the total area in this region and 93% of the total population. Three sources of raw material, sugarcane, oil palm, and municipal solid wastes (MSW) were considered for bioenergy production, considering liquid biofuels (ethanol and biodiesel), and bioelectricity.

The remainder of the section offers basic information on the six small island developing states (SIDS) whose present and prospective sustainable bioenergy potential were evaluated. The current situation of these countries is briefly described based on their socio-economic and energy indicators and current land use situation.

1.1. SOCIO-ECONOMIC CONDITIONS IN CARIBBEAN SIDS

The SIDS were first recognised as a distinct group of developing countries at the June 1992 United Nations Conference on Environment and Development, held in Rio de Janeiro. The Caribbean is one of three geographic zones (Figure 1) in which the world's SIDS are distributed: the other zones are the Pacific, as well as the Atlantic, the Indian Ocean and the South China Sea (AIS). From a global perspective, the SIDS are a distinct group containing 39 states and 18 associate members of United Nations (UN) regional commissions. They are home to approximately 65 million people and face unique social, economic and environmental vulnerabilities (Thomas *et al.*, 2020).

Figure 1 SIDS around the world, with the Caribbean SIDS highlighted



Source: (Thomas *et al.*, 2020).
Note: SIDS = small island developing states.

Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

While the SIDS differ significantly in terms of land area, systems of government, economic development and geographic characteristics, they share several particularities; this led the United Nations to recognise them as a group with its own characteristics, including fossil fuel reliance, restricted industrial activity and limited economies of proportion (Atkinson *et al.*, 2022).

The Caribbean region is made up of nearly 7 000 islands, islets, reefs and cays spread over an extensive geographical area and encircled by the Caribbean Sea and the Atlantic Ocean. It is a tropical maritime region, with two climatic seasons per year – wet and dry – with temperatures varying between 25°C in the winter and 32°C in the summer (Fuller *et al.*, 2020). The Caribbean SIDS are a distinct conglomerate of 26 developing countries that face similar sustainable development challenges, including, for example, growing population, restricted resources, distance, vulnerability to natural phenomena, fragility to external shocks, disproportionate dependence on international trade and a fragile environment.

According to the United Nations Development Programme (UNDP, 2022), the Caribbean SIDS include 16 UN members and 10 non-UN members/associate members of regional commissions (Table 1). The majority of these nations are islands (larger and small), while three are continental lands (Belize, Guyana and Suriname). The SIDS are home to more than 39 million inhabitants (91% in the five larger countries). Some countries are fully reliant on imported energy, whereas some export oil and natural gas (Aruba, Trinidad and Tobago and, more recently, Guyana) (Surroop *et al.*, 2018).

Table 1 Demography, economy and human development indicators of the Caribbean SIDS

CARIBBEAN SIDS	SOVEREIGNTY	STATES	SURFACE AREA (km²)	POPULATION (1 000 PEOPLE)	GDP PER CAPITA (USD 1 000)	HDI
Anguilla	United Kingdom	Non-member	91	14	-	-
Antigua and Barbuda	Independent	UN member	422	89	14.45	0.778
Aruba	Netherlands	Non-member	180	105	30.25	-
Bahamas	United Kingdom	UN member	13 878	393	28.61	0.814
Barbados	Independent	UN member	430	283	15.19	0.814
Belize	Independent	UN member	21 759	324	4.44	0.716
Bermuda	United Kingdom	Non-member	4 000	64	117.1	-
British Virgin Islands	United Kingdom	Non-member	151	30	-	-
Cayman Islands	United Kingdom	Non-member	264	66	91.39	-
Cuba	Independent	UN member	109 884	11 271	9.1	0.777
Curaçao	Netherlands	Non-member	444	155	19.7	-
Dominica	Independent	UN member	751	72	6.53	0.742
Dominican Republic	Independent	UN member	48 192	10 277	7.27	0.756
Grenada	Independent	UN member	344	105	9.68	0.779
Guyana	Independent	UN member	214 969	795	6.96	0.682
Haiti	Independent	UN member	27 750	10 174	1.18	0.51
Jamaica	Independent	UN member	10 991	2 769	4.66	0.734
Montserrat	United Kingdom	Non-member	102	4.65	12.38	-
Saint Kitts and Nevis	Independent	UN member	261	54	17.44	0.779
Saint Lucia	Independent	UN member	539	181	9.28	0.759
Sint Maarten	France	Non-member	54	85	29.16	-
Saint Vincent and the Grenadines	Independent	UN member	389	109	7.3	0.738
Suriname	Independent	UN member	163 820	535	6.49	0.738
Trinidad and Tobago	Independent	UN member	5 130	1 337	15.38	0.796
Turks and Caicos Islands	United Kingdom	Non-member	948	38	23.88	-
US Virgin Islands	United States	Non-member	347	87	38.13	0.894

Source: (Surroop *et al.*, 2018; UNDP, 2022; World Bank, 2022).

Note: GDP = gross domestic product; HDI = Human Development Index; km² = square kilometre; SIDS = small island developing states.

In recent decades, the Caribbean SIDS have undergone rapid demographic, social, economic and political transformations. Since the early 2000s, the majority of this region's countries have made considerable progress in lowering poverty rates. The current median poverty in the Caribbean SIDS is approximately 26%, but it is as high as 77% in Haiti, and 36% in Grenada and Guyana (FAO, 2021). Human Development Index rankings underwent negative evolution in most Caribbean SIDS (Fuller *et al.*, 2020). Likewise, economic development in the Caribbean SIDS has not been integrative, and assessments of inequality, multi-dimensional progress and poverty reveal numerous differences and disadvantages (Scobie, 2022). The majority of the Caribbean SIDS are middle-income countries. The per capita gross domestic product (GDP) ranges from USD 1 180 in Haiti to USD 38 130 in the US Virgin Islands (World Bank, n.d.). Many Caribbean SIDS, which relied primarily on agricultural production, have switched to relying on tourism and service-related activities over the past two decades. Nevertheless, economic diversification continues to be a target to be achieved in several of this region's countries (Atkinson *et al.*, 2022).

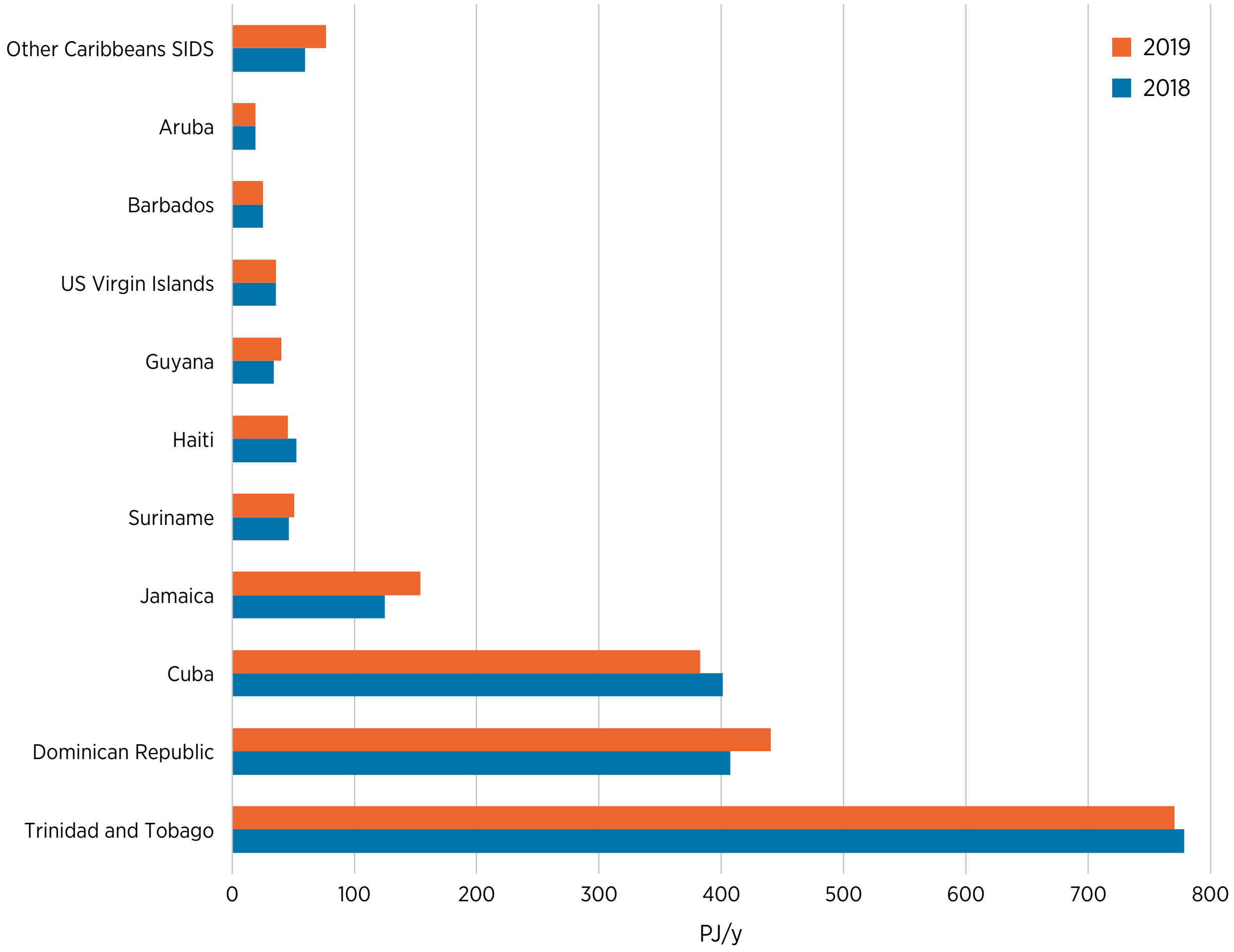
1.2. ENERGY SITUATION IN THE CARIBBEAN SIDS

The Caribbean SIDS consumed 2 041 petajoules (PJ) of energy in 2019; this is an increase of 2.76% over 2018 (Figure 2). Six countries account for nearly 90% of the region's primary energy consumption. Trinidad and Tobago stands out, with a 37.8% share of primary energy consumption, which is essentially due to its important petrochemical industry.

The energy matrix of most Caribbean SIDS reveal the predominance of fossil fuels in the region. Fossil fuels represent 97% of the region's primary energy consumption (petroleum derivatives 55% and natural gas 38%) (Figure 3). This picture, however, is strongly influenced by the high consumption in Trinidad and Tobago. Meanwhile, the modest share of renewable energies (2.56%) is noteworthy.

Providing affordable energy access is one of several challenges faced by governments and communities in the Caribbean SIDS. The majority rely on imported fossil hydrocarbons (Figure 4, excluding Anguilla, Bahamas, Curaçao and Sint Maarten, due to lack of data), essentially petroleum derivatives, for power generation and transportation. These energy sources are associated with direct economic costs, provisioning risks and other indirect costs due to climate change (Atteridge and Savvidou, 2019). In this sense, increased and potentially fluctuating combustible costs, along with increased transportation prices, antiquated grid infrastructure that leads to technical and commercial losses, and dependence of diesel generators, result in Caribbean SIDS experiencing a significant rise in power costs as compared to other nations (Raghoo *et al.*, 2018).

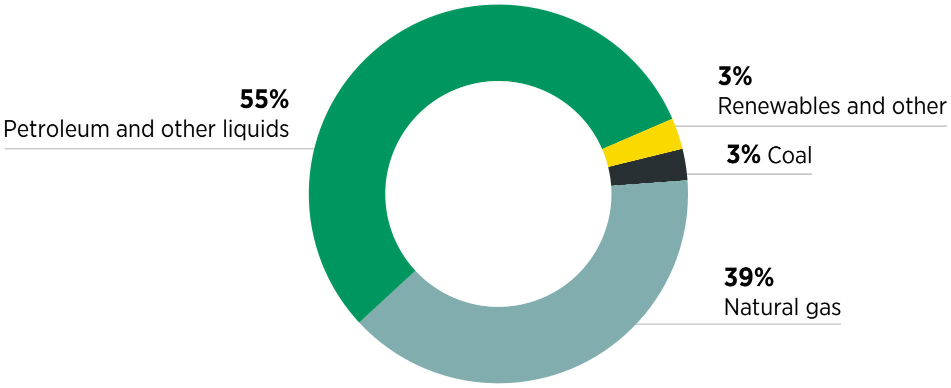
Figure 2 Total energy consumption of the Caribbean SIDS, 2018 and 2019



Source: (EIA, 2022a) data from the base year, 2019.

Note: SIDS = small island developing states; PJ/y = petajoules/year.

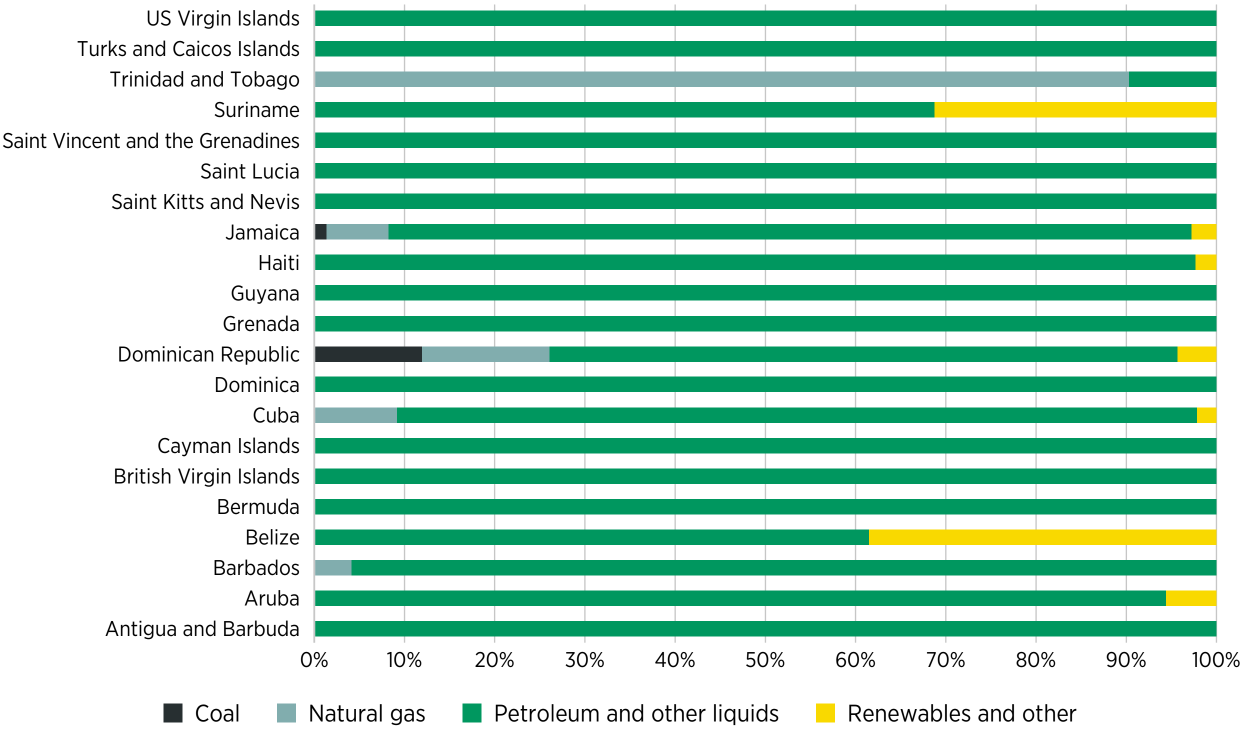
Figure 3 Final energy consumption for the Caribbean SIDS by source, 2019



Source: (EIA, 2022a).

Note: SIDS = small island developing states.

Figure 4 Energy consumption patterns of the Caribbean SIDS



Based on: (EIA, 2022a) data from the base year, 2019.

Note: SIDS = small island developing states.

Given the energy sector's direct relation with social, economic and environmental objectives, special attention on this sector must be included in the national development plans of most Caribbean SIDS. These priorities correspond to those of the Sustainable Development Goals (SDGs), especially SDG 7 of the United Nations 2030 Agenda (UN, 2021), the mitigation commitments made in the Paris Agreement through their respective Nationally Determined Contributions (Mohan, 2022) and declarations like the SIDS Accelerated Modalities of Action Pathway (SAMOA) pathway, which emphasises access to affordable and modern energy services, renewable energy and energy efficiency as key aspects of SIDS' sustainable development strategies (UNDP, 2016). Consequently, such goals will contribute to the reduction of energy dependence on imported sources, giving each nation greater autonomy and control over its energy market.

The Caribbean SIDS have promising renewable energy potential, especially for solar radiation, wind, hydropower, geothermal and biomass. This potential, indicated by the installed renewable generation capacity in this region (Table 2), favours the deployment of sustainable solutions. According to the platform (IRENA, 2022c), the Caribbean SIDS had approximately 4.02 gigawatts (GW) of installed renewable energy capacity at the end of 2020 (excluding Belize, Guyana and Suriname). This installed capacity includes over 1 235 megawatts (MW) of solar photovoltaics, 613 MW of wind, 1 057 MW of hydropower and 1 113 MW of bioenergy. This indicates that most Caribbean SIDS are theoretically capable of harnessing different alternative energy technologies that are well suited to the limited space and the region's soil and climatic characteristics.

Installed renewable energy capacity was highest for bioenergy (1.12 GW), which represented 30% of the total capacity. The cogeneration systems of sugar mills accounted for 99.5% of this capacity, while biogas generation accounted for 0.5%.

In summary, although the Caribbean SIDS have been increasingly adopting renewable energy sources, essentially for generating electricity, national energy demand continues to rely on imported oil products, for all uses and especially for the mobility of people and goods, as indicated in Figure 4. Liquid biofuels have been considered in certain countries, such as Jamaica, although with limited effective results.

Table 2 Installed renewable energy capacity in the Caribbean SIDS (MW)

CARIBBEAN SIDS	SOLAR	WIND	HYDRO	BIOENERGY
Anguilla	1.51	-	-	-
Antigua and Barbuda	12.86	4.00	-	-
Aruba	13.60	30.00	-	2.00
Bahamas	2.54	-	-	-
Barbados	68.88	1.16	-	-
Belize	6.55	0.02	56.95	35.50
Bermuda	-	-	-	-
British Virgin Islands	1.17	0.80	-	-
Cayman Islands	13.70	-	-	-
Cuba	257.95	11.75	71.90	951.36
Curaçao	16.12	47.25	-	-
Dominica	0.32	0.24	6.64	-
Dominican Republic	697.62	417.05	625.14	47.43
Grenada	3.60	0.08	0.00	-
Guyana	6.65	0.08	2.37	42.37
Haiti	2.61	0.02	77.99	-
Jamaica	92.55	99.00	30.00	32.13
Montserrat	1.00	-	-	-
Saint Kitts and Nevis	2.25	2.20	-	-
Saint Lucia	3.84	-	-	0.18
Sint Maarten	-	-	-	-
Saint Vincent and the Grenadines	3.68	-	5.71	-
Suriname	11.73	-	180.18	1.50
Trinidad and Tobago	4.00	0.01	-	-
Turks and Caicos Islands	0.94	-	-	-
US Virgin Islands	9.99	0.10	-	-

Based on: (IRENA, 2022c).

Note: MW = megawatt; SIDS = small island developing states.

1.3. AGRICULTURE AND LAND USE IN THE CARIBBEAN SIDS

Agricultural activity accounts for less than 1% of the GDP of diverse Caribbean nations, although it continues to be a crucial sector of the economy of other nations such as Haiti, the Dominican Republic, Cuba, Jamaica and Trinidad and Tobago, where over 66%, 50%, 58%, 40% and 10% of the national area, respectively, is designated as land for the use of this sector (Table 3). Agricultural activity contributes only 7%-17% of the GDP of the above countries, but it stands out due to its significant contribution to jobs (typically 10%-25%, and almost 50% in Haiti) (Fuller *et al.*, 2020).

Table 3 Land use distribution in the Caribbean SIDS

CARIBBEAN SIDS	LAND USE (km^2)						
	AL	TCr (% AL)	TMP (% AL)	TF (% AL)	PCr (% AL)	PMP (% AL)	FL
Anguilla	-	-	-	-	-	-	55.00
Antigua and Barbuda	90.00	33.7	5.2	5.5	11.1	44.4	81.80
Aruba	20.00	75.9	11.6	12.4	-	-	4.20
Bahamas	140.00	43.4	6.7	7.1	28.6	14.3	5 098.60
Barbados	100.00	53.2	8.2	8.7	10.0	20.0	63.00
Belize	1 720.00	39.7	6.1	6.5	18.6	29.1	12 882.10
Bermuda	3.00	75.9	11.6	12.4	-	-	10.00
British Virgin Islands	70.00	10.8	1.7	1.8	14.3	71.4	36.20
Cayman Islands	27.00	5.6	0.9	0.9	18.5	74.1	12.72
Cuba	64 010.00	22.3	1.9	21.2	10.2	44.4	32 420.00
Curaçao	-	-	-	-	-	-	0.70
Dominica	250.00	18.2	2.8	3.0	68.0	8.0	478.70
Dominican Republic	24 290.00	27.4	4.2	4.5	14.6	49.3	21 360.10
Grenada	80.00	28.5	4.4	4.7	50.0	12.5	177.00
Guyana	12 412.50	25.7	3.9	4.2	3.2	62.9	184 245.00
Haiti	18 400.00	44.2	44.2	44.2	44.2	44.2	3 504.10
Jamaica	4 440.00	20.5	3.1	3.4	21.4	51.6	5 930.00
Montserrat	30.00	50.6	7.8	8.3	33.3	-	25.00
Saint Kitts and Nevis	60.00	83.3	0.0	0.0	1.7	15.0	110.00
Saint Lucia	106.00	14.0	3.3	9.6	69.4	3.7	207.70
Sint Maarten	-	-	-	-	-	-	-
Saint Vincent and the Grenadines	70.00	21.7	3.3	3.5	42.9	28.6	285.40
Suriname	840.00	56.0	8.6	9.2	6.0	19.0	152 085.00
Trinidad and Tobago	540.00	35.2	5.4	5.7	40.7	13.0	2 286.10
Turks and Caicos Islands	10.00	75.9	11.7	12.4	-	-	105.20
US Virgin Islands	33.00	20.7	3.2	3.4	6.1	66.7	197.60

Source: (FAO, 2023) data from the base year, 2019.

Note: AL = agricultural land; FL = forest land; km^2 = square kilometres; PCr = land designated for permanent crops; PMP = land designated for permanent meadows and pastures; SIDS = small island developing states; TCr = land designated for temporary crops; TF = land with temporary fallow; TMP = land designated for temporary meadows and pastures.

Yet, as a preliminary assessment, looking at Table 3 shows that several Caribbean SIDS have sufficient land for expanding bioenergy crops – when considering the share of land suitable and available, for instance, for temporary meadows and pastures, temporary fallow, and permanent meadows and pastures. These crops could play a crucial role in helping the Caribbean SIDS ensure affordable access to low-carbon energy for their inhabitants. There are multiple options to generate energy using biomass as a source. The most important crops for bioenergy production (traditional or modern) in the Caribbean region are sugar cane (molasses, bagasse, straw and vinasse), cassava (peels, leaves, stems and cassava wastewater), coconuts (shell and husk), oil palm fruit (fibre, shell, empty fruit bunch and palm oil mill effluent), coffee (husk and spent coffee grounds) and cocoa (husk). One interesting potential feedstock is sargassum seaweed which countries like Belize and Barbados are assessing its potential as a biofuel through research/pilot projects (Thompson *et al.*, 2020). The disposal/use of sargassum is going to become of increased relevance for Caribbean SIDS as global warming persists. The bioenergy produced through solid waste processing (urban and industrial) can also be considered.

1.4. SELECTION CRITERIA

Table 4 describes the criteria that were adopted to define a set of Caribbean SIDS countries in order to assess their sustainable bioenergy generation potential.

Table 4 Criteria and the countries selected for the assessment of bioenergy potential

CRITERIA	RATIONALE	LIMITS	COUNTRIES SELECTED (IN ORDER OF SIZE/VOLUME/ DEGREE BY INDIVIDUAL CRITERIONS)
Land area of country	To consider larger territories, with potentially more land available for biomass production	Total area greater than 2 500 km^2	Guyana, Cuba, the Dominican Republic, Belize, Jamaica, Trinidad and Tobago, Haiti
Population	To consider a larger population, where bioenergy systems can promote more benefits	Total population greater than 1 million	Cuba, Haiti, the Dominican Republic, Puerto Rico, Jamaica, Trinidad and Tobago
National energy consumption	To consider relevant energy markets, where the impact of bioenergy matters	A set of countries that represent at least 80% of the regional energy consumption of the Caribbean small island developing states	Trinidad and Tobago, the Dominican Republic, Puerto Rico, Jamaica, Cuba
Sovereignty of country	To consider states that are able to define and implement energy programs		All independent states

The Caribbean SIDS are a heterogeneous and diversified set of nations and states. The countries selected account for about 94% of the total area of this region, and about 93% of its population. Given the above criteria, the following countries were selected for a detailed assessment of sustainable bioenergy potential: Cuba, the Dominican Republic, Jamaica, Trinidad and Tobago and Guyana.

While Cuba, Dominican Republic, and Jamaica depend largely on energy imports for their domestic demand at same time that they have active sugarcane agro-industry; previous attempts were made to adopt ethanol as fuel in Cuba and the Dominican Republic, and ethanol blends reached regular use (E10) in Jamaica. These are aspects that reinforce these countries' interest in developing their own bioenergy production systems, and the selection of Trinidad and Tobago, and Guyana deserves some justification (Gutiérrez *et al.*, 2020; Johnson *et al.*, 2020).

Trinidad and Tobago is well known as a significant exporter of natural gas, as well as the largest energy consumer in the Caribbean SIDS. Its inclusion in the detailed assessment was necessary to ensure that the selected countries represent at least 80% of the region's energy demand. Guyana, the largest country in the Caribbean SIDS, is opening promising frontiers of offshore oil production, but also has vast land for agriculture. Both Trinidad and Tobago and Guyana are traditional sugar producers since colonial times.

1.5. SUSTAINABILITY AND REQUIREMENTS OF MODERN BIOENERGY SYSTEMS

As indicated by the International Renewable Energy Agency (IRENA) in the *World Energy Transitions Outlook* (WETO 2022), limiting the global temperature increase will require bioenergy to play a decisive role. By the year 2050, sustainable bioenergy production must grow from 34 exajoules in 2020 to 135 EJ in 2050 (IRENA, 2023). To reach these challenging goals, it is essential to pay strict attention to sustainability principles, as stressed in the biomass report by IRENA in 2022 (IRENA, 2022b):

> The production and use of bioenergy must be managed with care, however. Sustainability concerns about production and consumption are major issues in the bioenergy industry. They pose risks to investors and discourage policy makers from making bioenergy a major pillar of their strategies for reaching 1.5°C targets. Other factors to consider include the potential competition between energy and other uses and the need to include appropriate sustainability constraints – in particular, the extent to which land can be used to grow energy crops while preserving food security and biodiversity. Increased demand for bioenergy, as well as biomass as a chemical feedstock, will also influence supply. Some economic thresholds may also need to be applied.

To ensure the sustainability of bioenergy, especially concerning the expansion of dedicated energy crops as explored in this study, it's crucial to take into account the broader context of land management, emphasising the interconnectedness between various land covers and uses on a landscape level. The goal is to strike a harmonious balance between the imperative for agricultural expansion and the preservation of vital ecological functions, such as safeguarding biodiversity, securing water supply and maintaining soil health. Decision makers must be mindful of the inherent uncertainties and limitations within estimates provided in this study. This study intends to provide estimates for preliminary consideration, and they remain adaptable to evolving conditions in specific local contexts.

2. BIOENERGY POTENTIAL IN CARIBBEAN SIDS

For selected members of the Caribbean SIDS, three raw material sources for bioenergy production are considered in this study:

1. Sugarcane, considered for all countries, is a well-known crop developed since the colonial period.

2. Oil palm is considered only for Cuba and the Dominican Republic.

3. Municipal solid waste (MSW), considered for all six countries.

Among all the crops with bioenergy potential, adoption was the highest for sugarcane and palm, since they adapted well to the soil and climate conditions in the region, besides having high productivity, in terms of volume of production per cultivated area and bioenergy per cultivated area. As highlighted in the previous chapter, although these crops offer high energy yields, an essential selection criterion, their adoption as energy sources and the subsequent energy development must follow strict sustainability criteria and consider biodiversity protection, and soil and water resource conservation, besides including production that benefits social welfare and is closely monitored and evaluated by the government. In this sense, within the scope of the global energy agro-industry, there are bad examples to avoid and good examples to be adopted.

Assessing a nation's potential to generate bioenergy from various crops involves determining how much land is accessible and the expected yield per hectare. The next sections present an assessment of land suitable and available for sugarcane and oil palm, and the yield model adopted to estimate the annual feedstock production. For MSW, the annual potential production is linked to population and variables such as geographic factors and socio-economic level.

To consider the conversion to bioenergy carriers (*e.g.* ethanol, biodiesel and electricity), different technology scenarios are assumed for each feedstock, as described in Table 5, which also presents the key findings for each feedstock in this study.

Table 5 Scenarios, technologies and key findings for sustainable bioenergy development in the Caribbean SIDS

SCENARIO	TECHNOLOGY	KEY FINDINGS
SUGARCANE		
Business as usual (C0)	A distillery annex was simulated with a conventional cogeneration system (a back pressure turbine and a low-efficiency boiler), based on the current sugarcane yield.	• In some countries, the potential expansion of sugarcane production is limited to preserve the forestry coverage, as observed in Guyana, whereas in other countries, the agricultural area is relatively limited, for example, in Trinidad and Tobago. The countries with the highest supply potential are Cuba, Haiti and the Dominican Republic, where over 21 million tonnes (Mt) could be produced annually. • The availability of raw materials such as sugarcane molasses, which can be easily processed for producing ethanol, a biofuel seamlessly blendable with gasoline and compatible for use in conventional vehicles without modification, offers a favourable starting point to promote modern bioenergy. • The utilisation of sugarcane bagasse and straw as combustibles in thermoelectric power plants has enormous potential to boost power production and broaden the energy mix of Caribbean small island developing states (SIDS). This could reduce fuel imports for electricity generation and improve electricity supply, contributing to carbon emissions mitigation.
Business as usual with improved sugarcane yield (C1)	The same system as above was simulated; however, improved yields were adopted (an increase of ±60% over current production).	
New framework – without irrigation (C2)	An autonomous distillery was simulated with a modern cogeneration system (condensation and extraction steam turbine), assuming sugarcane yield without irrigation.	
New framework – with irrigation (C3)	The same system as above was simulated, although assuming yield with irrigation.	
OIL PALM		
Business as usual (C0)	A palm oil mill (without biodiesel production) and a cogeneration system (a back pressure turbine and a low-efficiency boiler) were assumed.	• This oil crop is produced and industrially processed only in the Dominican Republic, where 20 kilohectares is available for producing 54 kilotonnes (kt) of crude palm oil and 7.5 kt of crude palm kernel oil per year. There is favourable potential to increase productivity. • Considering the usual scale of the oil palm agro-industry, this study considered palm oil for bioenergy goals solely for the Dominican Republic and Cuba. • In scenarios C2 and C3, Cuba and the Dominican Republic could immediately displace, respectively, 26%-43% and 10%-17% of the overall diesel consumption using half of the potential crude palm oil production as feedstock to produce biodiesel. • The utilisation of solid biomass from oil palm (fibre, shell and empty fruit bunch) as a combustible in thermoelectric power plants has excellent potential to improve power production and transform the Dominican Republic's and Cuba's energy mix.
Business as usual with improved yield (C1)	The same industrial system as in the previous scenario and a higher-yield palm oil were assumed.	
New framework – with average productivity (C2)	A biodiesel plant annexed to the palm oil mill was adopted, with a modern cogeneration system (condensation and extraction steam turbine), a covered lagoon for effluent treatment and current average yield.	
New framework – with improved productivity (C3)	The same characteristics as in the C2 scenario were adopted but with higher oil palm yield.	

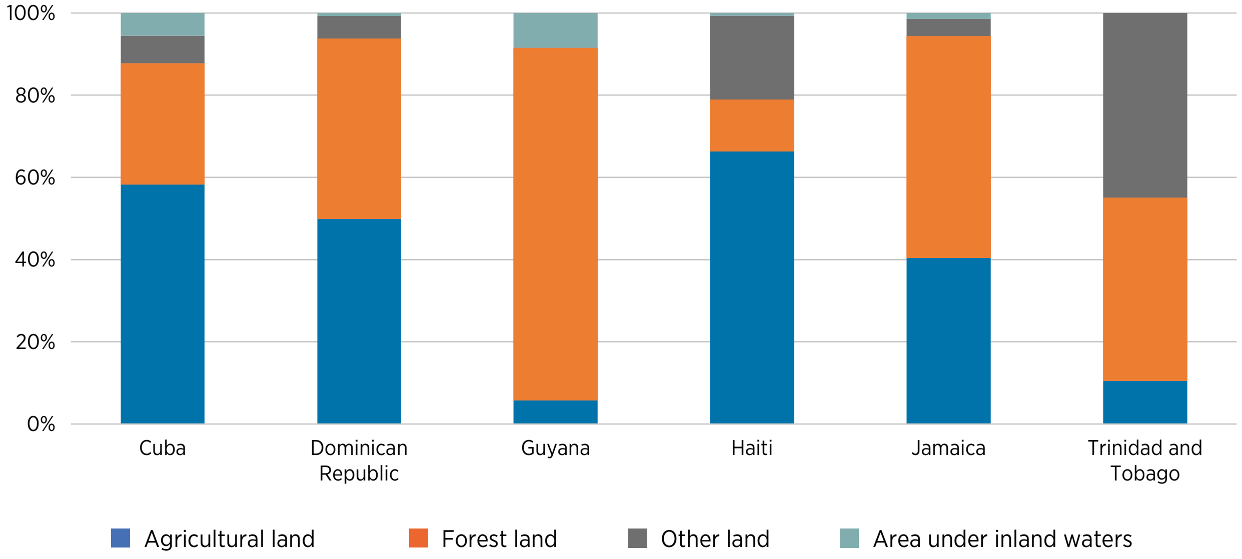
Table 5 Continued

MUNICIPAL SOLID WASTE (MSW)		
Waste-to-energy via landfill gas (C1)	The MSW treatment technique used in this scenario was landfill gas (LFG) recovery, with biomethane being burnt in alternative internal combustion engines.	• In the SIDS countries, adequate final disposal of MSW is a major challenge: only a few nations dispose of their MSW in sanitary landfills. Open-air dumpsites are the prevailing MSW disposal mechanism (~80%), which generates serious environmental issues. • LFG-based energy generation potential is the highest for Cuba and the Dominican Republic (over 313 GWh per year and over 290 GWh per year, respectively) since they are the most populous Caribbean islands and have the highest solid waste generation and energy consumption. Guyana, Haiti, Jamaica and Trinidad and Tobago have lower LFG-based energy generation potential; they could substitute 1.46%, 7.57%, 2.44% and 0.93% of their electricity consumption, respectively. • The potential energy production from the direct combustion of MSW showed a substantial increase over potential LFG-based energy production for all the assessed Caribbean countries. However, incineration is the most unlikely scenario, due to high investment and environment management costs.
Waste-to-energy via direct combustion (incineration) (C2)	For this scenario, direct combustion treatment coupled with a Rankine cycle, which uses a steam turbine to generate electricity, was used.	

2.1. LAND AVAILABLE AND APPROPRIATE FOR BIOENERGY PRODUCTION

An area of 41.7 million hectares (Mha) of the Caribbean countries are being assessed. Within this mix, Guyana has the largest area, with 21.5 Mha, followed by Cuba (10.9 Mha), the Dominican Republic (4.8 Mha), Haiti (2.7 Mha), Jamaica (1 Mha) and Trinidad and Tobago (0.5 Mha). Together, these countries represent more than 75% of the total area covered by the Caribbean SIDS. The areas of these countries are distributed across forestry and agriculture, are under inland waters and also include built-up areas and land used for aquaculture, for example. Figure 5 shows the distribution of the area in each country.

Figure 5 Main types of land coverage in Caribbean countries



Based on: (FAO, 2023) data from the base year, 2019.

The premises to delimitate and quantify the potential areas for expansion were constructed based on legal restrictions and environmental guidelines, which guide how territories are occupied and utilised. The first restriction applied, based on data obtained from the Food and Agriculture Organization (FAO, 2021), was the exclusion of conservation units and indigenous lands, and urban areas. Areas under inland waters were subsequently excluded.

Among the remaining areas, those whose agricultural land suitability is classified as inadequate (land under permanent meadows and pastures) and those that are currently occupied by agriculture (land under permanent crops) were disregarded, because no changes in land use are expected in these areas. Finally, from the remaining areas, those with land under temporary crops were also excluded. The result obtained indicates a potential area of 1.48 Mha in Cuba, 0.28 Mha in the Dominican Republic, 0.10 Mha in Guyana, 0.26 Mha in Haiti, 0.03 Mha in Jamaica and 0.01 Mha in Trinidad and Tobago for expanding the bioenergy crops frontier; most of this area already presents anthropic use and is classified as land under temporary meadows and pastures, and land with temporary fallow, as detailed in Table 6. It is worth noting that these lands, according to FAOSTAT, are hypothetically suitable for crop development (because these areas are classified as cropland); however, there is a probability that land of this type is in a state of degradation or in a degraded state (because they are lands with meadows, pastures and fallows). Therefore, it is possible that there is some area in which the productivity levels noted in this study have not been reached and needs a specific evaluation through complementary studies.

Note that the potential areas for expanding bioenergy production represent a modest fraction of the land areas of the Caribbean countries considered in the study. Moreover, these areas are within arable land, *i.e.* they possess the soil and climatic qualities for the optimal development of several energy crops.

2.2. SUGARCANE'S BIOENERGY POTENTIAL

Sugarcane, known for its high yields, is processed using modern technology, presents interesting potential for bioenergy production and has undergone several modifications throughout history (Pereira *et al.*, 2018). Sugarcane is a species of the grass family and a semi-evergreen. It is grown in regions roughly in the middle of the Earth (tropical and subtropical zone) (Table 7). Commercial sugarcane varieties are complex hybrids, which are derived through intensive selective breeding between the species *Saccharum officinarum* L. and *Saccharum spontaneum* L. (O'Hara and Mundree, 2016).

Table 6 Potential area for expanding bioenergy crops and the corresponding land percentage by Caribbean city

CARIBBEAN SIDS	POTENTIAL AREA FOR EXPANSION (kha)	FRACTION OF TOTAL LAND AREA (%)
Cuba	1 479.90	14.25
Dominican Republic	332.09	6.87
Guyana	101.71	0.51
Haiti	259.13	9.40
Jamaica	29.06	2.68
Trinidad and Tobago	7.95	1.55

Source: (FAO, 2023) data from the base year, 2019.

Note: kha = kilohectare; SIDS = small island developing states.

Table 7 Edaphic characteristics of sugarcane

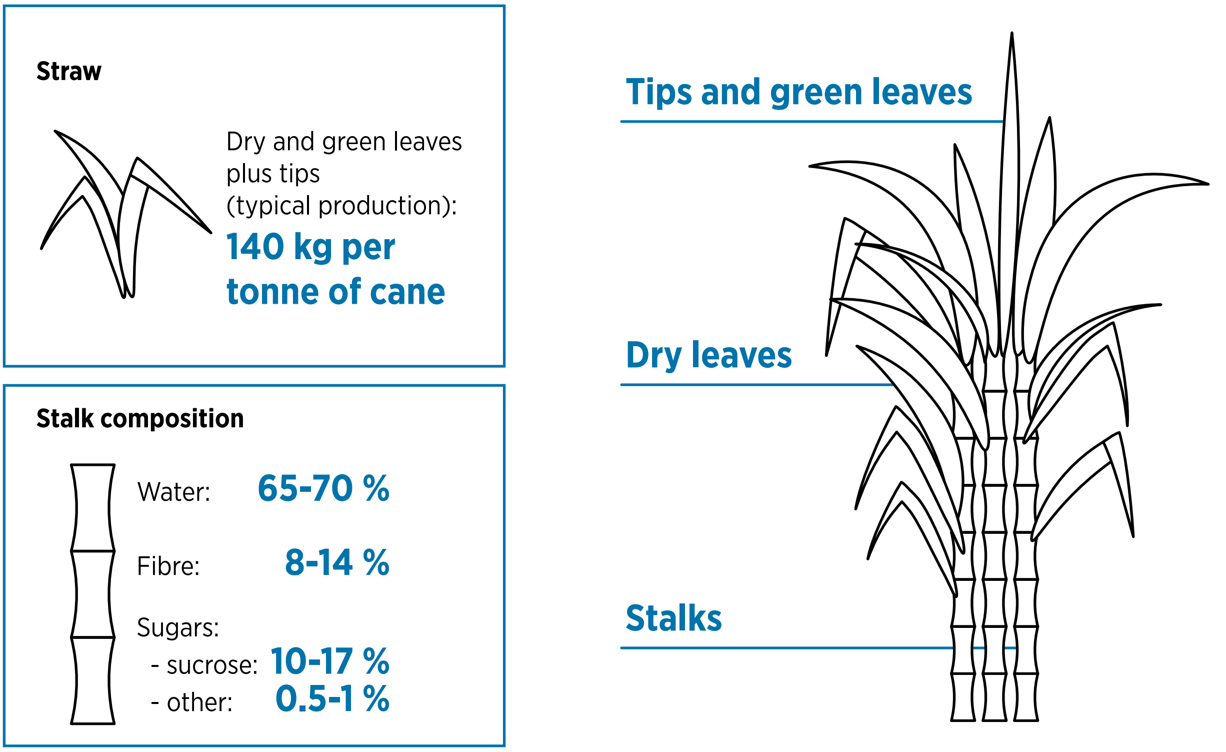
EDAPHIC FACTORS	SUGARCANE	UNIT
Climate	Tropics and subtropics	-
Location	33°N and 33°S	Longitude and latitude
Annual precipitation	600-3 000	mm
Temperature	25-32	°C
Dry season	-	Months
Solar radiation	18-36	MJ/m^2
Wind	<18	m/s
Principal soil types for cultivation	Oxisols, aridisols, alfisols, argisols	-

Source: (Santos *et al.*, 2015).

Note: m^2 = square metre; MJ = megajoule; mm = millimetre; s = second.

The main feature of sugarcane is its use in the production of sugars (mainly sucrose, glucose and fructose), which are concentrated in its stem. The aboveground part of the plant comprises the stem, green leaves and dry leaves. The aerial part of the plant contains a higher proportion of moisture than the part below ground. The aerial part thus has green leaves, whereas the portion below ground has dry (or dead) leaves. Harvested stalks have about 70% moisture, and the dry matter is principally sucrose and lignocellulose, as indicated in Figure 6. Under favourable soil and climatic conditions, the marketable sugarcane crop yield is 80 000 to 110 000 kilogrammes per hectare (kg/ha); this is well below the theoretical maximum of approximately 470 000 kg/ha under optimal conditions (Cortez *et al.*, 2018), but well over the 25 000 to 35 000 kg/ha yield seen under unfavourable conditions of water stress, deficient soils and inadequately advanced technology.

Figure 6 Typical sugarcane biomass composition



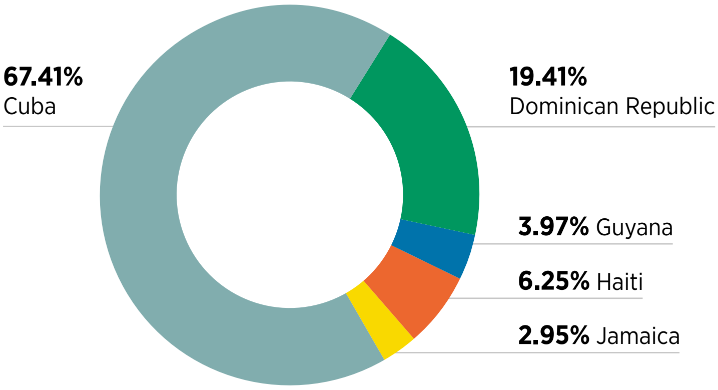
Source: (IRENA, 2019a).

Note: kg = kilogramme.

The Caribbean has long been known as a region for sugarcane cultivation. Sugarcane is used as feedstock mainly for sugar production. Its subproducts, like bagasse and molasses, are used to produce steam/electricity (self-consumption of mills) and alcoholic liquor, respectively (Khan and Khan, 2019). In 2019, according to the FAO (FAO, 2023), over 25 million tonnes (Mt) of sugarcane were processed in 2019 (Figure 7). Cuba is the undisputed leader in sugarcane processing in the Caribbean region (67%), followed by the Dominican Republic (19%), Haiti (6%), Guyana (4%) and Jamaica (3%).

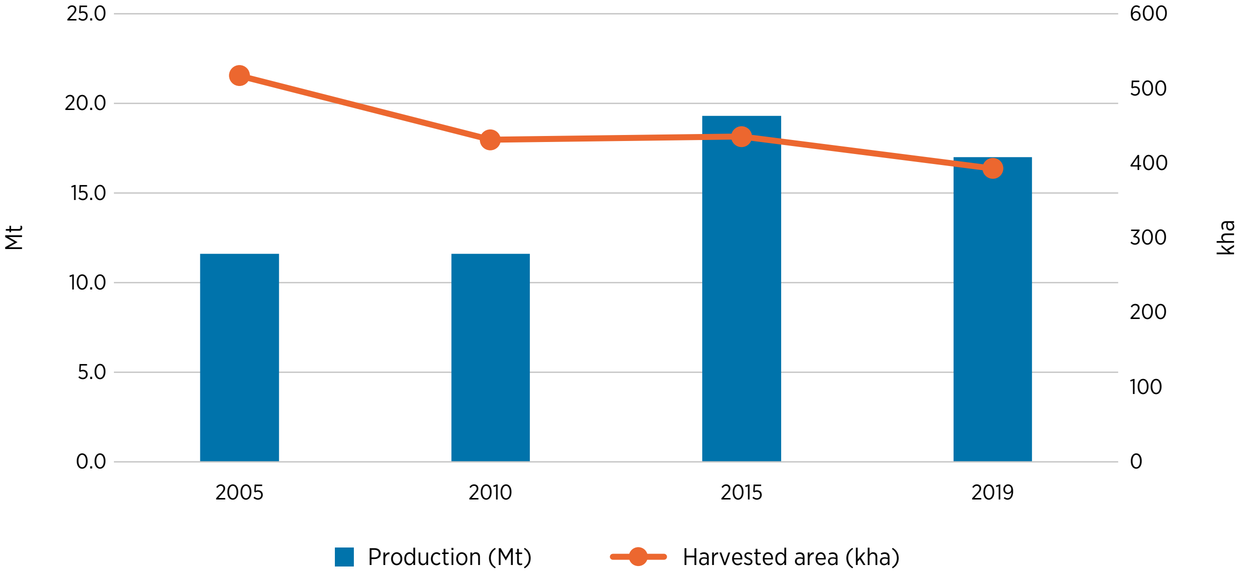
Cuba has historically been a sugarcane-producing nation. Prior to 1990, Cuba processed approximately 82 Mt of sugarcane per year, with an average yield of 57 500 kg/ha (Alonso-Pippo *et al.*, 2008). Inappropriate policies, geopolitical shifts (Khan *et al.*, 2019), degrading infrastructure and disasters caused by natural phenomena caused a 39% decline in Cuba's average sugarcane yield in 2005, down to 22.4 t/ha. However, a series of improvement measures for sugarcane harvesting and processing (*e.g.* machinery renovation, complete automation of the manufacturing process and installation of better equipment, new investments in refineries to reduce steam consumption by thermal insulation of heat exchangers and piping) have led to an improvement in the average productivity of the country's sugarcane agro-industry recently (~36%, in 2019) (AZCUBA, 2022), as shown in Figure 8.

Figure 7 Proportion of sugarcane processing in the Caribbean SIDS



Based on: (FAO, 2023) data from the base year, 2019.
Note: SIDS = small island developing states.

Figure 8 Sugarcane production and harvested area in Cuba, 2005-2019

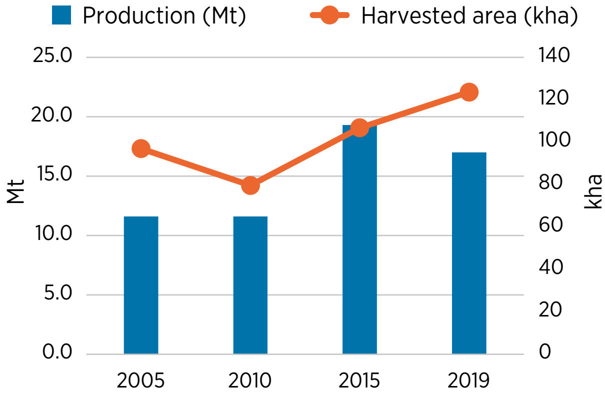


Based on: (FAO, 2023) data from the base year, 2019.
Note: kha = kilohectare; Mt = million tonne.

Figures 9, 10, 11 and 12 show the sugarcane production trend and the area harvested over the past 14 years for the Dominican Republic, Guyana, Haiti and Jamaica (FAO, 2023). The cultivated area has grown since 2010 in the Dominican Republic. Sugarcane processing, however, has not kept pace with this growth. This is because the Dominican Republic has only four active sugar factories (Central Romana, Cristóbal Colon, Barahona [CAC] and Azucarera Porvenir), which limits productivity (USDA GAIN, 2022). For Guyana, a sharp decline in sugarcane production (~36%) and cultivated area (~37%) can be observed; this is due to socio-economic issues, labour shortages, unseasonable weather, a drastic decline in demand from the European Union and the permanent closure of several mills (Guyana Chronicle, 2020). Jamaica shows the same trend as Guyana. Political changes, degrading infrastructure and disasters caused by natural phenomena led to a 20.6% decline in Jamaica's average sugarcane yield in 2019, down to 47.4 tonnes/ha (Figure 13).

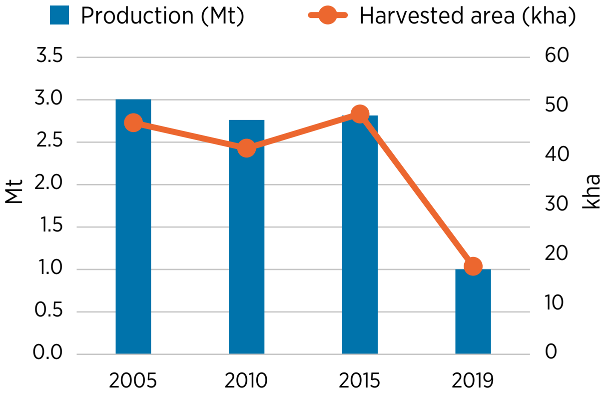
The situation is different for Haiti, as can be observed in Figure 11. Sugarcane production and area cultivated increased 50% and 35%, respectively, in Haiti. This growth is related to diverse financial support through projects focused on strengthening the irrigation infrastructure and providing flood protection, and subsidies to promote technology transfer and sustainable agricultural practices, alongside the improvement of services such as phytosanitary controls and support for land regularisation measures (Banco Interamericano de Desarrollo, 2022).

Figure 9 Sugarcane production and harvested area in the Dominican Republic



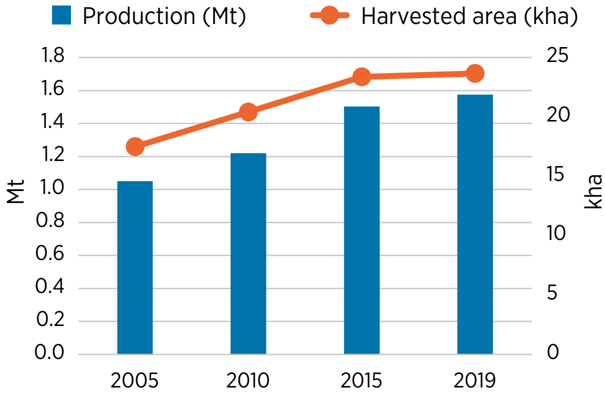
Based on: (FAO, 2023) data from the base year, 2019.
Note: kha = kilohectare; Mt = million tonne.

Figure 10 Sugarcane production and harvested area in Guyana



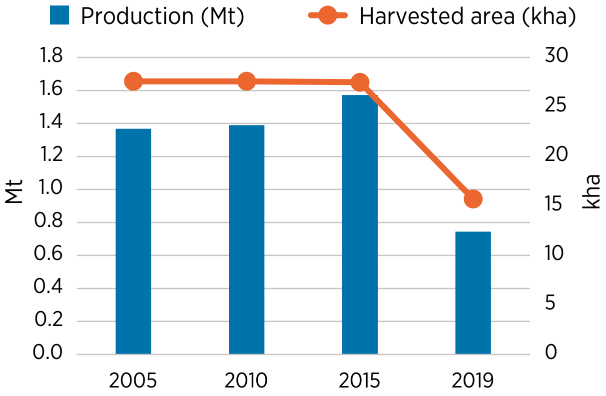
Based on: (FAO, 2023) data from the base year, 2019.
Note: kha = kilohectare; Mt = million tonne.

Figure 11 Sugarcane production and harvested area in Haiti



Based on: (FAO, 2023) data from the base year, 2019.
Note: kha = kilohectare; Mt = million tonne.

Figure 12 Sugarcane production and harvested area in Jamaica



Based on: (FAO, 2023) data from the base year, 2019.
Note: kha = kilohectare; Mt = million tonne.

Finally, Trinidad and Tobago is not currently processing sugarcane industrially for energy since the economy is characterised by the availability of natural sources of fossil fuel such as oil and natural gas. However, sugarcane and its products, such as sugar, molasses and rum, which are rudimentarily cultivated and processed, are other important products for island trade, albeit on a smaller scale. However, financial incentives are expected to reactivate the agro-energy sector (Política Exterior, 2019).

Sugarcane production potential mainly depends on soil and climate conditions. Hence, this study estimated sugarcane yield as a function of precipitation and temperature by implementing Eq. (1), which considers as the most sensitive parameters the frequency of warm days and the heat intensity on those days, and water available to sugarcane root systems in the soil (IRENA, 2019a):

$$Y_{Clim+Irrig} = 80.0 + 0.01\,DD - 0.1(1 - IR)HD \tag{1}$$

In the equation, IR is the irrigation ratio (IR = WI/HD), WI is water supplied annually by irrigation (millimetres, [mm]), DD is degree days, for a base temperature of 20°C (°C-day), HD is annual hydric deficiency, for a 100 centimetre soil depth (mm), and $\mathrm{Y}_{\mathrm{Clim+Irrig}}$ is the average yield of sugarcane stalks considering climate and irrigation (t/ha). Note that the amount of water supplied by irrigation should not exceed the water deficiency; irrigation should thus range from 0 (no irrigation) to 1 (irrigation at maximum level and no yield reduction) (IRENA, 2019a).

Table 8 summarises the data and modelled yield estimates for the Caribbean SIDS. The estimated yields are in the range observed in the Caribbean region and in other Central American and Caribbean countries (Cutz *et al.*, 2013).

The yield model developed above, as well as other similar simplified models implemented in large areas (Alejandra Moreno *et al.*, 2018; Rudorff and Batista, 1990; Teodoro *et al.*, 2015), has limitations in the cases of specific harvest production (IRENA, 2019a) and is also limited by changes in climatic conditions (mainly the increase in the frequency and intensity of extreme weather events, especially droughts) (Carvalho *et al.*, 2015; Hussain *et al.*, 2019). Agriculture scientists and decision makers, therefore, must work closely to mitigate the potential adverse effects of climate change on agriculture and improve sugarcane yields. In their efforts, they should follow through multi-disciplinary approaches, including, among others, continued development of new sugarcane cultivars through genetic improvement and molecular biology, and improved best management practices. Nevertheless, the model described is a useful tool for estimating average yields, as required in this study.

Table 8 Sugarcane yield modelling data and results for Caribbean SIDS

CARIBBEAN SIDS	SELECTED SITE	CO-ORDINATES		DD (°C-day)	RAINFALL (mm)	HD (mm)	YIELD (t/ha)	
		LATITUDE	LONGITUDE				NOT IRRIGATED	IRRIGATED
Guyana	Georgetown	6°48’ N	58°9’ W	2 222.9	2 226	115	90.73	102.23
Cuba	Santa Clara	22°24’ N	79°57’ W	1 776.4	1 300	200	77.76	97.76
Dominican Republic	Santo Domingo	18°29’ N	69°55’ W	2 033.6	1 525	160	84.34	100.34
Haiti	Barahona	18°9’ N	71°4’ W	2 665.7	1 024	310	75.66	106.66
Jamaica	Mona	39°48’ N	111°51’ W	2 980.8	1 286	206	89.21	109.81
Trinidad and Tobago	Port of Spain	10°40’ N	61°30’ W	2 688.0	2 100	125	94.38	106.88

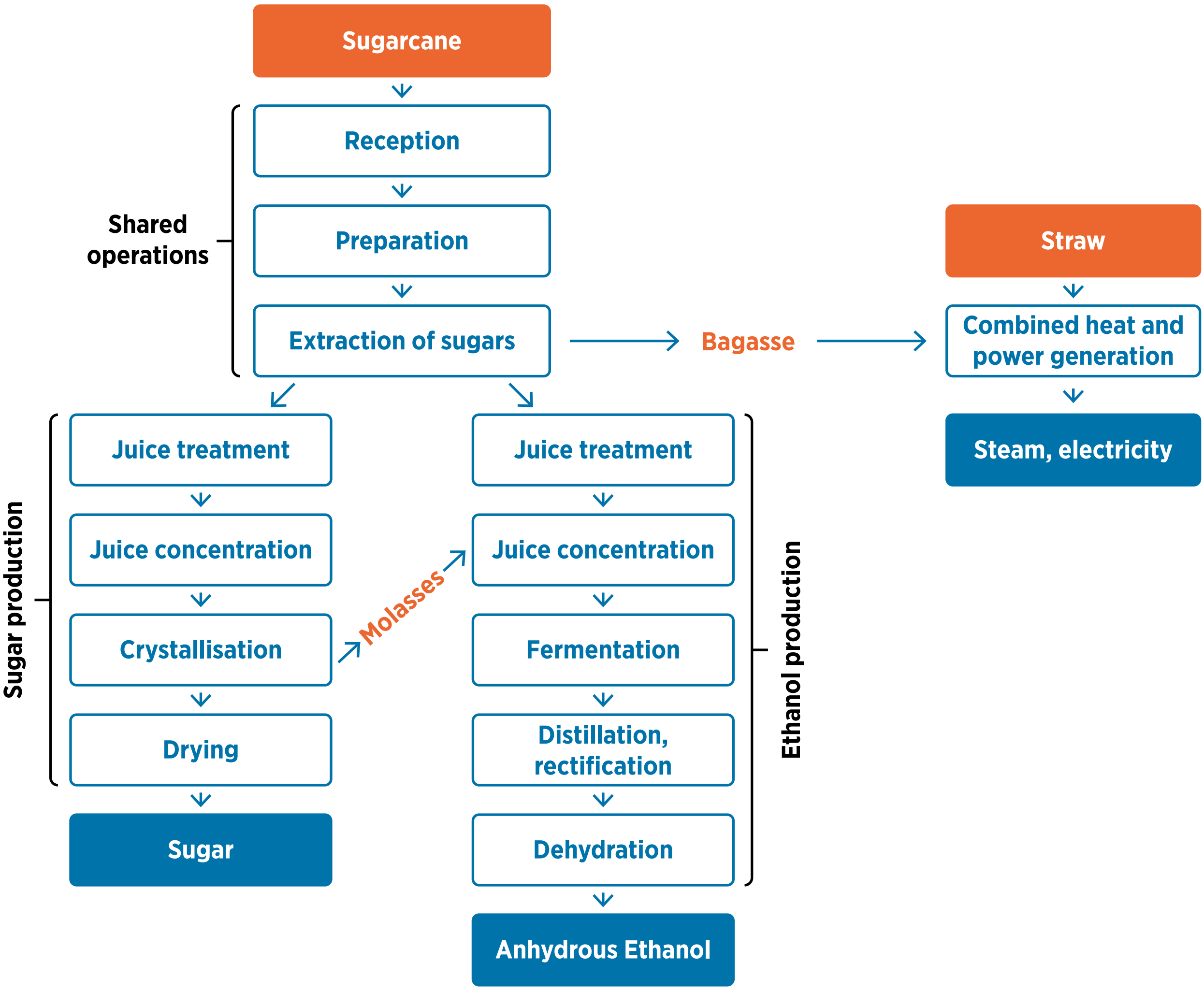
Note: DD = degree days, for a base temperature of 20°C (°C-day); HD = annual hydric deficiency, for a 100-centimetre soil depth (mm); mm = millimetre; SIDS = small island developing states; t/ha = tonne/hectare.

2.2.1. Industrial schemes for the production of sugar, ethanol and power

Bioethanol can be made comparatively easily from sugar than starchy feedstock. An aqueous solution of sugar can be fermented directly to an alcoholic solution, which can then be distilled to produce fuel-grade ethanol. This watery substance, known as molasses, is a co-product of sugar production. Therefore, in all countries where commercial production of ethanol from sugarcane has been introduced, it has started in the sugar mills with molasses as a raw material. Mills produce ethanol and sugar jointly, in percentages that vary based on the relative prices. The initial processing phases for ethanol production are the same as for sugar production, as shown in Figure 13. If ethanol is produced simultaneously with sugar, the distillery is called "annexed"; and if all sugarcane juice is converted for ethanol, without sugar production, the distillery is called "autonomous".

Conventional sugarcane-based sugar and ethanol production involves the common processes of cane collection, cane conditioning and juice extraction, which precede sugar and ethanol generation. The extracted juice is forwarded to purification, where impurities are filtered out, providing a material that is suitable for the subsequent stages. Although most juice purification stages are similar for sugar and ethanol production, each technique has its particularities. In a sugar factory, crystallisation of sugar (molasses) produces a concentrated sweet solution, which is a fermentable by-product. The sugarcane juice from the juice treatment phase of ethanol production is then mixed with molasses (when available) and fermented using yeast (which is recuperated and reutilised in the fermentation process). The ethanol-containing fermentation product (wine) is forwarded for distillation and dehydration. In the sugar factory, the juice is concentrated, crystallised, centrifuged and dried.

Figure 13 General diagram for sugarcane-based sugar and ethanol production (first generation)



Source: (Dias *et al.*, 2015).

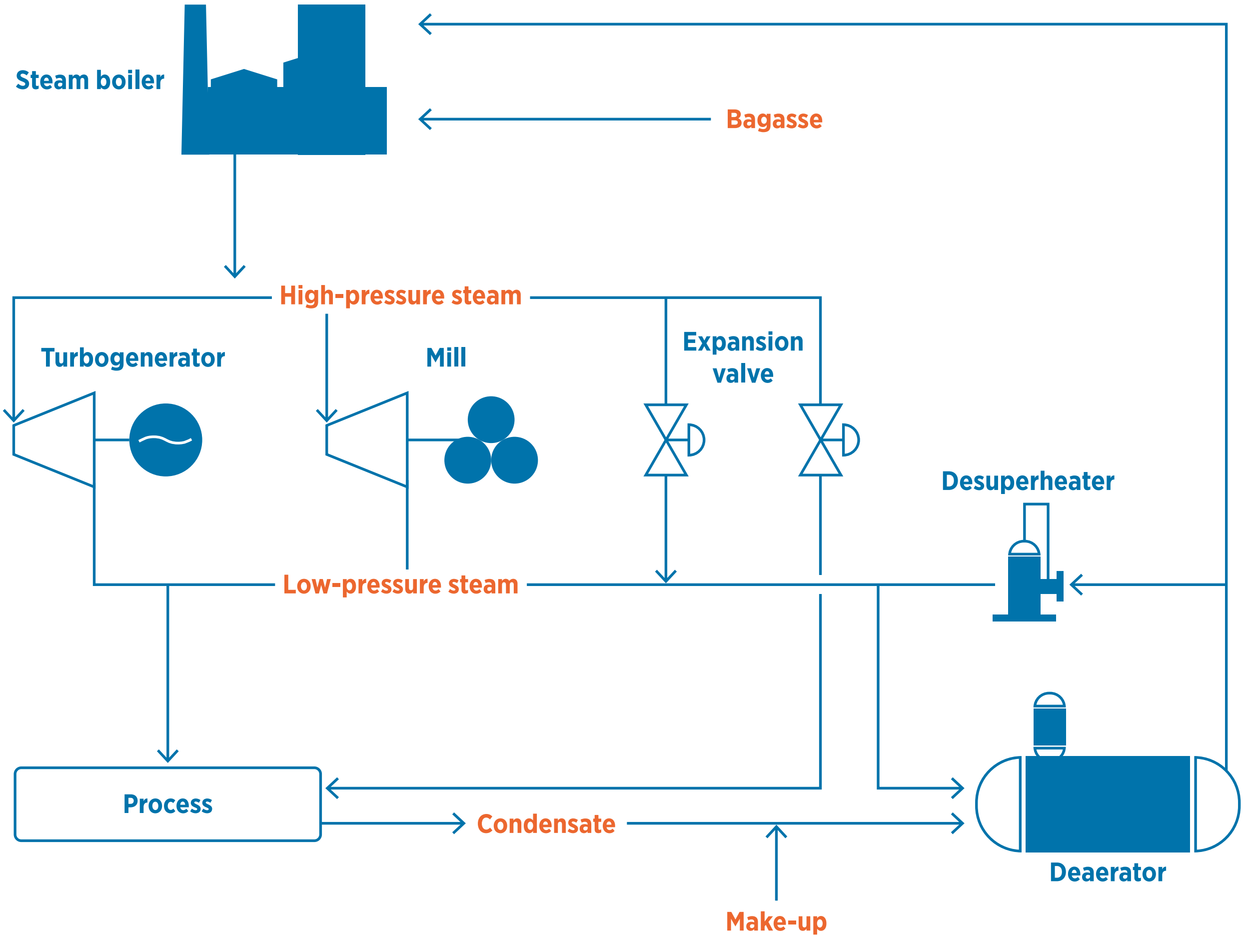
2.2.2. Cogeneration from bagasse and sugarcane straw

Sugarcane factories utilise three types of energy: thermal energy, for heating and concentration processes; mechanical energy, for milling and other mechanically driven systems; and electrical energy, for the operation of pumping, control and lighting systems. Sugarcane bagasse is used as a fuel to meet all these energy needs. It is used to produce electricity and heat via cogeneration. No external energy supply is required, and the surplus electricity generated can be sold through the power grid.

Figure 14 depicts a common combined heat and power system in the sugarcane agro-industry. The high-pressure steam from burning bagasse is fed to steam turbines to produce electricity (and to directly drive mills if there are no electric motors). Low-pressure steam emanating from the turbines helps meet the thermal energy needs. Generally, the power plant's steam system is balanced, so that the steam supply covers the plant's energy needs. Large amounts of supplementary electricity can be produced for sale to the public grid, more specifically by reducing low-pressure steam consumption, optimising boiler efficiency and steam characteristics (by increasing pressure and temperature) and increasing the biofuel available to the boilers (by incorporating sugarcane straw).

Table 9 presents how the technical characteristics of the cogeneration system's steam boilers affect surplus production in the sugarcane mills – either in the form of energy, that is, electricity, or bagasse. It presupposes the generation of 280 kg of bagasse (at a moisture content of 50%) per tonne of sugarcane, low-pressure steam for the process at 2.5 bar and the implementation of back pressure steam turbines. It also indicates the effect of using as fuel in the boilers 50% of the sugarcane straw available in the field – which would mean an effective contribution of 70 kg of this biofuel per tonne of sugarcane cut.

Figure 14 Common set-up of a cogeneration system in the sugarcane agro-industry



Source: (Seabra and Macedo, 2011).

Table 9 Electricity and bagasse surplus in cogeneration schemes in sugarcane mills

STEAM BOILER PARAMETERS	PROCESS STEAM CONSUMPTION (kg/t_{cane})	SUGARCANE STRAW USE	TOTAL ELECTRICITY OUTPUT (kWh/t_{cane})	ELECTRICITY SURPLUS (kWh/t_{cane})	BAGASSE SURPLUS (kg/t_{cane})
21 bar, 300°C	500	No	31.7	10.4	33
42 bar, 400°C	500	No	55.4	25.4	50
65 bar, 480°C	500	No	87.6	57.6	13
65 bar, 480°C	350	No	101.6	71.6	0
65 bar, 480°C	500	50%	169.7	139.7	33
65 bar, 480°C	350	50%	183.0	153.0	0

Source: (IRENA, 2019a).

Note: kg = kilogramme; kWh = kilowatt hour; t = tonne.

It is worth pointing out that the implementation of efficient cogeneration systems, with the sale of surplus electricity to public utilities, will be contingent on the existence of an appropriate regulatory framework. The electricity system must allow connecting sugar mill plants to the grid, promote such connection by means of fair market prices (reflecting the combination of generation costs in the grid), foresee technical co-ordination for the grid to operate smoothly and protect both energy producers and utilities.

The development of this normative framework in several countries (*e.g.* Brazil, Uruguay, Ecuador and the Dominican Republic) has yielded notable results, and sugarcane energy meets an essential portion of the countries' needs.

2.3. SCENARIOS FOR SUGARCANE BIOENERGY PRODUCTION

To explore the situation in a context similar to the current one and with a potential breakthrough in the sugar-energy industry, the potential supply of biofuel and electricity from sugarcane in the Caribbean SIDS was estimated for four scenarios, combining two scenarios for raw materials and two scenarios for processing. First, two reference scenarios were developed, corresponding to an annexe distillery; these were denominated C0 (*business as usual*) and C1 (*business as usual with improved sugarcane yield*). In both cases, the objective is to represent, as faithfully as possible, the most widespread technology in the Caribbean sugarcane industry, which is (1) a traditional distillery annexe for sugar and ethanol production (ethanol derived from molasses in C0 and equal fractions of the juice [50/50] are utilised for ethanol and sugar production in C1; and (2) cogeneration systems with back pressure turbines for self-consumption (electricity for the system and steam to drive the mills). The practice of pre-burning in harvesting is considered, to eliminate all the straw in the field. Typically, the mill uses only a fraction of the available bagasse (about 90%) as fuel in the cogeneration plant, so as to leave some bagasse to *start* boilers in the next harvest season.

Table 10 Description of the main parameters in the adopted scenarios

SCENARIOS	SUGARCANE PLANTS	CHARACTERISTICS
C0	Annex distillery, conventional cogeneration plant and current yield	• Current area used for cultivation: differs by country [ha.y] • Current productivity: differs by country [t/ha.y] • Ethanol productivity: 15 [l/t of cane] • Steam consumption: 420 [kg/t of cane] • Electricity surplus: 10.4 [kWh/t of cane] • Mills powered by a steam turbine and a back pressure steam turbine
C1	Annex distillery, conventional cogeneration plant, improved yield	• Current area used for cultivation: differs by country [ha.y] • Improved productivity: differs by country [t/ha.y] • Ethanol productivity: 32 [l/t of cane] • Steam consumption: 420 [kg/t of cane] • Electricity surplus: 10.4 [kWh/t of cane] • Mills powered by a steam turbine and a back pressure steam turbine
C2	Autonomous distillery, modern cogeneration plant, yield without irrigation	• Potential area for expansion: differs by country [ha.y] • Productivity without irrigation: differs by country [t/ha.y] • Ethanol productivity: 85 [l/t of cane] • Steam consumption: 360 [kg/t of cane] • Electricity surplus: 123 [kWh/t of cane] • Condensing/extraction steam turbine
C3	Autonomous distillery, modern cogeneration plant, yield with irrigation	• Potential area for expansion: differs by country [ha.y] • Irrigated Productivity: differs by country [t/ha.y] • Ethanol productivity: 85 [l/t cane] • Steam consumption: 360 [kg/t of cane] • Electricity surplus: 123 [kWh/t of cane] • Condensing/extraction steam turbine

Note: l = litre; kg = kilogramme; kWh = kilowatt hour; t = tonne; t/ha.y = tonne per hectare per year.

On the other hand, in the improved scenarios – denominated C2 (*new framework – without irrigation*) and C3 (*new framework – with irrigation*), corresponding to an autonomous distillery – bioenergy production (biofuel and bioelectricity) is prioritised. In both cases, the objective is to represent more efficient and mature technologies, which involve modern cogeneration plants (condensing/extraction steam turbine), use of all the bagasse and 50% of the straw generated, and electrified mills. Table 10 summarises the main technological characteristics adopted by scenario.

2.3.1. Current and potential sugarcane production

Table 11 presents sugarcane production in the Caribbean SIDS in 2019 (FAO, 2023) It also presents potential production assuming areas that could be utilised for expanding bioenergy crops and the country-wise estimated sugarcane productivity (see Table 12) for the studied scenarios. These values show the relevance of the current sugarcane industry and the relative importance of land that could be available for expanding sugarcane production, utilising a comparatively modest portion of the national territory. It is important to note that scenarios C2 and C3 assumed the use of 75% and 60% of the area available for expansion in Cuba and the Dominican Republic, respectively; in the case of the other countries, 100% of the available area was used.

Table 11 Current and potential sugarcane production in the Caribbean SIDS

CARIBBEAN SIDS	C0 [a]	C1	C2	C3	POTENTIAL PRODUCTION INCREASE IN RELATION TO C0 (%)		
	(10^3 t/y)				C1	C2	C3
Cuba	17 000.0	30 253.3	86 312.2	108 510.7	178.0	507.7	638.3
Dominican Republic	4 895.9	10 386.0	13 985.7	16 639.0	212.1	285.7	339.9
Guyana	1 002.3	1 616.4	9 228.4	10 398.1	161.3	920.7	1 037.4
Haiti	1 575.0	1 774.5	19 604.8	27 637.8	112.7	1 244.7	1 754.7
Jamaica	744.2	1 397.3	2 592.5	3 191.1	187.8	348.4	428.8
Trinidad and Tobago	-	-	750.2	849.6	-	-	-

Source: [a](FAO, 2023) data from the year 2019.

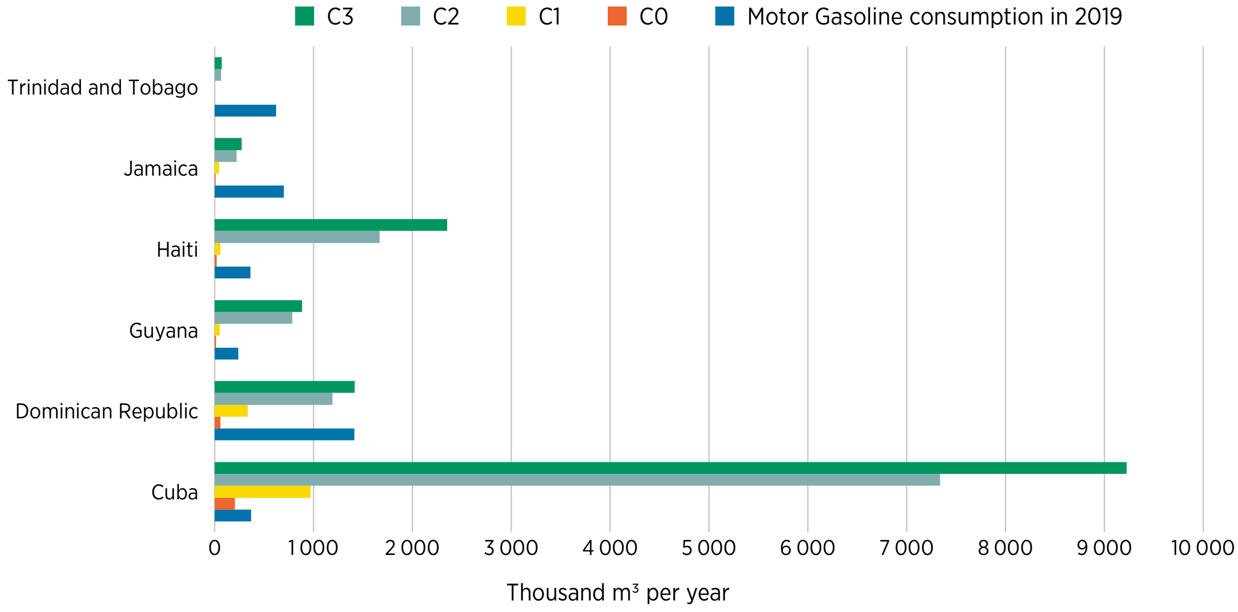
Note: C0 = business as usual; C1 = business as usual with improved sugarcane yield; C2 = new framework – without irrigation; C3 = new framework – with irrigation; SIDS = small island developing states.

While restrictions in land use transformation for sugarcane cultivation limit potential expansion in some countries, as observed in Guyana, in others, it is limited because the country is relatively small, for example, Trinidad and Tobago. The countries with the highest supply potential are Cuba, Haiti and the Dominican Republic, where over 21 Mt could be produced annually, even under the conservative hypotheses.

2.3.2. Potential sugarcane ethanol supply

Figure 15 presents potential ethanol supply in the Caribbean SIDS for all production scenarios. As expected, this potential varies by sugarcane production. For the six countries selected, total ethanol production was estimated to range from 0.2 million litres – with Cuba and the Dominican Republic accounting for, respectively, 67% and 19%, when considering the scenario of current availability of molasses (C0) – to 14.2 million litres, for the higher availability scenario (C3) – with Cuba and Haiti accounting for, respectively, 65% and 16%, when considering an expansion of sugarcane cultivated areas and a state-of-the-art conversion process. This biofuel production represents a large share of the current consumption of gasoline, as shown in Figure 15; exceptions are Trinidad and Tobago and Jamaica, where the domestic demand for gasoline exceeds the biofuel demand.

Figure 15 Potential ethanol supply in the four scenarios



Note: C0 = business as usual; C1 = business as usual with improved sugarcane yield; C2 = new framework – without irrigation; C3 = new framework – with irrigation; m³ = cubic metre.

Table 12 Potential ethanol supply in the four scenarios for sugarcane biofuel (1 000 m³/year)

CARIBBEAN SIDS	MOTOR GASOLINE CONSUMPTION IN 2019 [1 000 m³/y]*	C0 [1 000 m³/y]	C1 [1 000 m³/y]	C2 [1 000 m³/y]	C3 [1 000 m³/y]
Cuba	367	204	968	7 337	9 223
Dominican Republic	1 413	59	332	1 189	1 414
Guyana	237	12	52	784	884
Haiti	362	19	57	1 666	2 349
Jamaica	698	9	45	220	271
Trinidad and Tobago	619	0	0	64	72

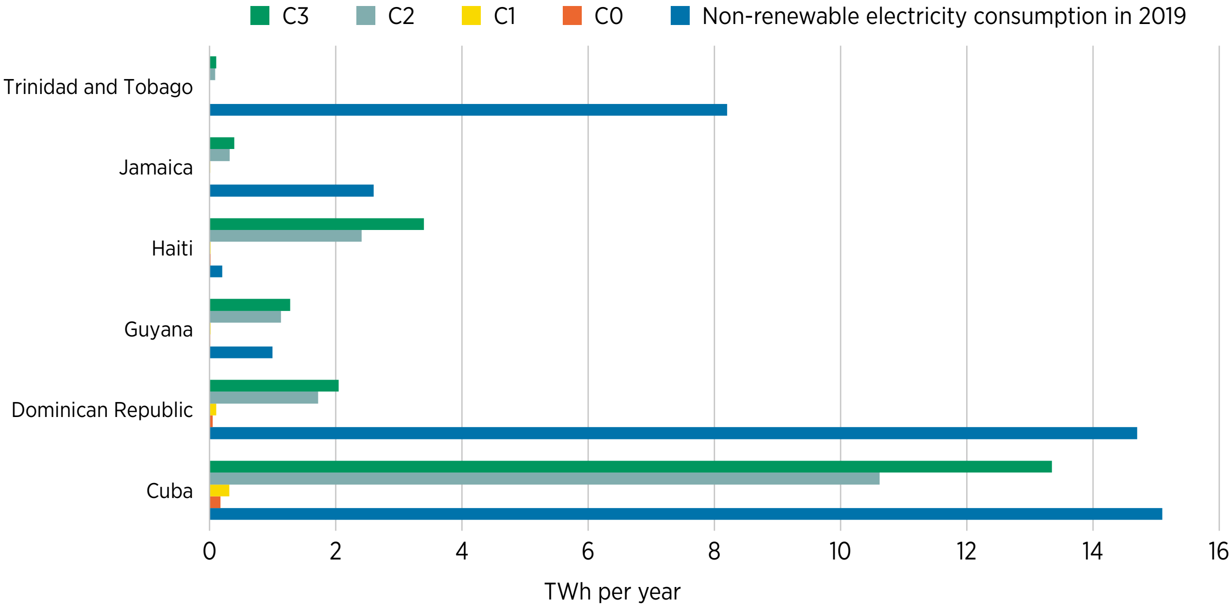
***Source:** (EIA, 2022a)

Note: C0 = business as usual; C1 = business as usual with improved sugarcane yield; C2 = new framework – without irrigation; C3 = new framework – with irrigation; m³ = cubic metre; SIDS = small island developing states.

2.3.3. Potential biopower supply from sugarcane bagasse and straw

The utilisation of residual biomass (bagasse and straw) from sugarcane as a solid combustible in thermoelectric power plants presents interesting potential to boost power generation and diversify the Caribbean SIDS' energy matrix. This would reduce fuel imports for electricity production, contribute to better electricity supply and help mitigate carbon emissions, as indicated further. Figure 16 and Table 13 present the potential bioelectricity supply in the Caribbean SIDS for the four scenarios.

Figure 16 Potential sugarcane bioelectricity supply in the four scenarios



Note: C0 = business as usual; C1 = business as usual with improved sugarcane yield; C2 = new framework – without irrigation; C3 = new framework – with irrigation; TWh = terawatt hour.

Table 13 Potential bioelectricity from sugarcane biomass (TWh/year)

CARIBBEAN SIDS	NON-RENEWABLE ELECTRICITY CONSUMPTION IN 2019 [TWh/y]*	C0 [TWh/y]	C1 [TWh/y]	C2 [TWh/y]	C3 [TWh/y]
Cuba	15.1	0.18	0.31	10.62	13.35
Dominican Republic	14.7	0.05	0.11	1.72	2.05
Guyana	1.0	0.01	0.02	1.14	1.28
Haiti	0.2	0.02	0.02	2.41	3.40
Jamaica	2.6	0.01	0.01	0.32	0.39
Trinidad and Tobago	8.2	-	-	0.09	0.10

***Source:** (EIA, 2022a)

Note: C0 = business as usual; C1 = business as usual with improved sugarcane yield; C2 = new framework – without irrigation; C3 = new framework – with irrigation; SIDS = small island developing states; TWh/y = terawatt hour per year.

Sugarcane-based bioelectricity could represent about 100% of Cuba's, Guyana's and Haiti's total electricity generation if a fraction of the fallow land (unused agricultural land), and meadow and pasture lands are used to expand sugarcane production. Otherwise, in the Dominican Republic, Jamaica and Trinidad and Tobago, bagasse and straw could represent, respectively, 14%, 15% and 1.2% of the countries' total electricity generation. Even with such lower contribution in these three countries, sugarcane provides an opportunity for their power sector to reduce its high dependence on natural-gas- and diesel-oil-based generation (EIA, 2022a).

2.4. OIL PALM'S BIOENERGY POTENTIAL

Elaeis guinensis (African oil palm), from which palm oil is extracted, is native to Africa's tropical zone. However, *Elaeis oleifera* (a species from the Americas) is a native Latin American species distributed from northern Mexico to the Amazon, as shown in Table 14. Palm oil is common in the traditional diets of African and Latin American and Caribbean natives, yet it is not the most widely consumed cooking oil.

Table 14 Edaphic characteristics of oil palm

EDAPHIC FACTORS	OIL PALM	UNIT
Climate	Tropical	-
Location	10°N and 10°S	Longitude and latitude
Precipitation	2 000-4 000	mm/year
Temperature	20-34	°C
Dry season	<4	Months
Solar radiation	14-21	MJ/m^2
Winds	<25	m/s
Principal soil types used for cultivation	Argisols, oxisols, vertisols	-

Source: (Corley and Tinker, 2003).

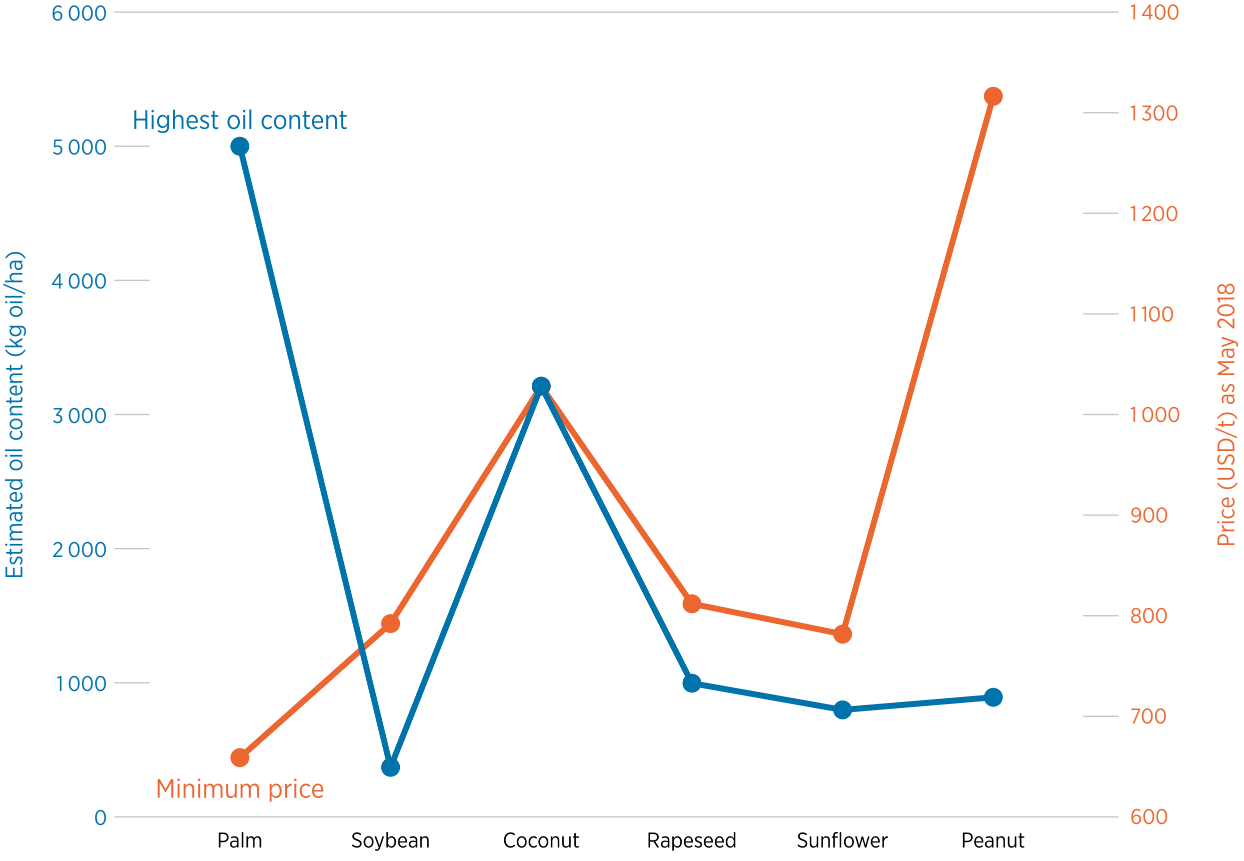
Note: m^2 = square metre; mm = millimetre; MJ = megajoule; s = second.

Oil palm is a crop of immense economic importance for several tropical developing countries. It is a high-yield oilseed crop that is profitable and reasonably simple to grow, for large industrial plantations as well as family farmers. Two types of oil are extracted from this oil crop and marketed: mesocarp oil, known as crude palm oil (CPO, most commonly utilised in a transesterification reaction); and kernel oil, known as crude palm kernel oil (CPKO). Generally, 4-5 t of CPO and 0.4-0.5 t of CPKO can be obtained from one cultivated hectare of oil palm (Garcia-Nunez *et al.*, 2016a).

Globally, palm oil is one of the most important vegetable oils traded in the market, with an annual world demand of 165 Mt, and this demand is projected to double by 2050 (Khatun *et al.*, 2017). This vegetable oil is frequently utilised in the food industry accounting for 50% of its applications, such as cooking oil and margarine. Additionally, 50% of the oil serves as an oleochemical, replacing mineral oil derivatives in various industries like detergent, cosmetics, pharmaceuticals/nutraceuticals, plastics, and lubricants, as well as biofuels (FAO, 2023).

About 3, 7 and 10 times more oil can be obtained from oil palm than coconut, rapeseed and soybean, respectively (Dey *et al.*, 2021) – its main contenders. These three crops also provide substantial non-oil products like coconut milk and soy protein meals as animal feed. The market price of palm oil is also lower (Figure 17), and it is one of the main sources for biomass production, mainly in the form of residues (fibre, nuts, wastewater, etc.). The demand surge for palm oil as a biofuel source (biodiesel) is driven by escalating oil prices and the deadline to achieve the targets outlined in various environmental agreements and successive "green" or renewable energy replacement initiatives. Further, as the growing concern for consumer health and the environment continues, by-products and subproducts of the palm oil agro-industry have led to the emergence of new industries (*e.g.* vitamins A and E, and other antioxidant health supplements from the oil; animal feed and organic fertilisers from the kernel; and sludge cakes from mill waste).

Figure 17 Variation of oil content and the market price of different vegetable oil feedstocks



Source: (Dey *et al.*, 2021).

Note: ha = hectare; kg = kilogramme; t = tonne.

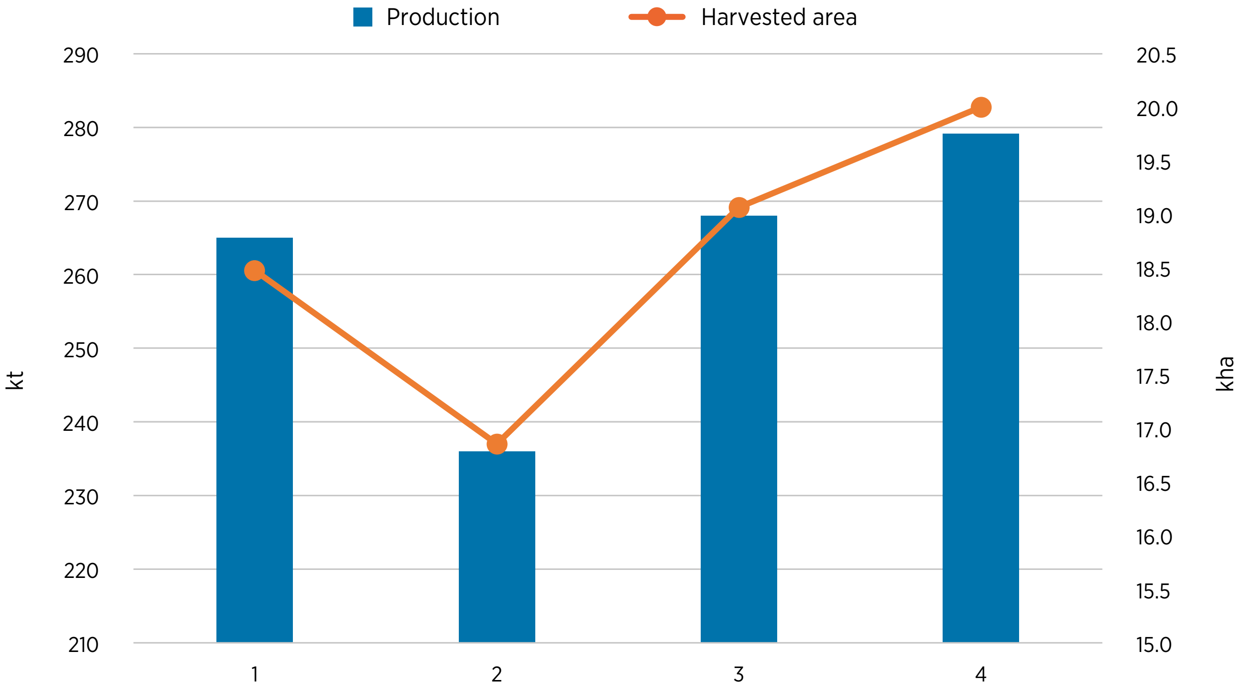
The palm oil agro-industry is a relevant producer of solid biomass residues. It produces roughly the equivalent of twice the quantity of CPO generated in a palm oil extraction plant (palm oil mill, POM). This solid biomass is composed of empty fruit bunches (EFBs), which are in a mass proportion of 22-25% of a fresh fruit bunch (FFB); fibres, which are in a mass proportion of 12-14% of an FFB; and palm kernel shell (PKS), which are in a mass proportion of 6-7% of an FFB (Ocampo Batlle *et al.*, 2020). The energy yield of palm oil biomass (EFB, PKS and fibre) is about 100 gigajoules/ha.year, equivalent to 37% of the energy contained in FFB, which is about 270 gigajoules/ha.year (Ocampo Batlle *et al.*, 2020). Nevertheless, much of these residues are meant to be returned to field as fertilisers and for soil regeneration. With careful management, this agro-industrial segment may have relevant energy potential. Moreover, it is considered the main instrument of socio-economic advancement, especially in rural areas of Malaysia and Indonesia, but also in other tropical areas of the American continent (*e.g.* Colombia, Ecuador and Peru). The palm oil industry employs, directly and indirectly, about 2 million people in Malaysia and about 5 million in Indonesia (Mat Yasin *et al.*, 2017).

Palm oil is currently produced and industrially processed only in the Dominican Republic, where 20 kilohectares (kha) are producing 54 kilotonnes (kt) of CPO and 7.5 kt of CPKO annually (FAO, 2021). As shown in Figure 18, the cultivated area for oil palm has grown at a rate of over 8% in the past 14 years. Such sustained growth has been achieved due, among other factors, to palm oil's good profitability and the high market demand for oil palm's products and by-products. But there exists immense potential to boost production by means of cultural and technological treatments, since these indicators are currently below optimum.

2.4.1. Oil palm yield

As the expansion of oil palm plantations can lead to the displacement of biodiverse rainforests, addressing the growing demand for palm oil primarily relies on two main strategies: improved productivity and selective expansion in degraded areas. Simply increasing productivity alone does not guarantee a reduction in deforestation, unless accompanied by supportive policies that are properly enforced. Nevertheless, enhancing productivity is a crucial step to alleviate pressure on the land and manage the environmental impact of palm oil production (Woittiez *et al.*, 2017).

Figure 18 Oil palm production and harvested area, Dominican Republic, 2005-2019



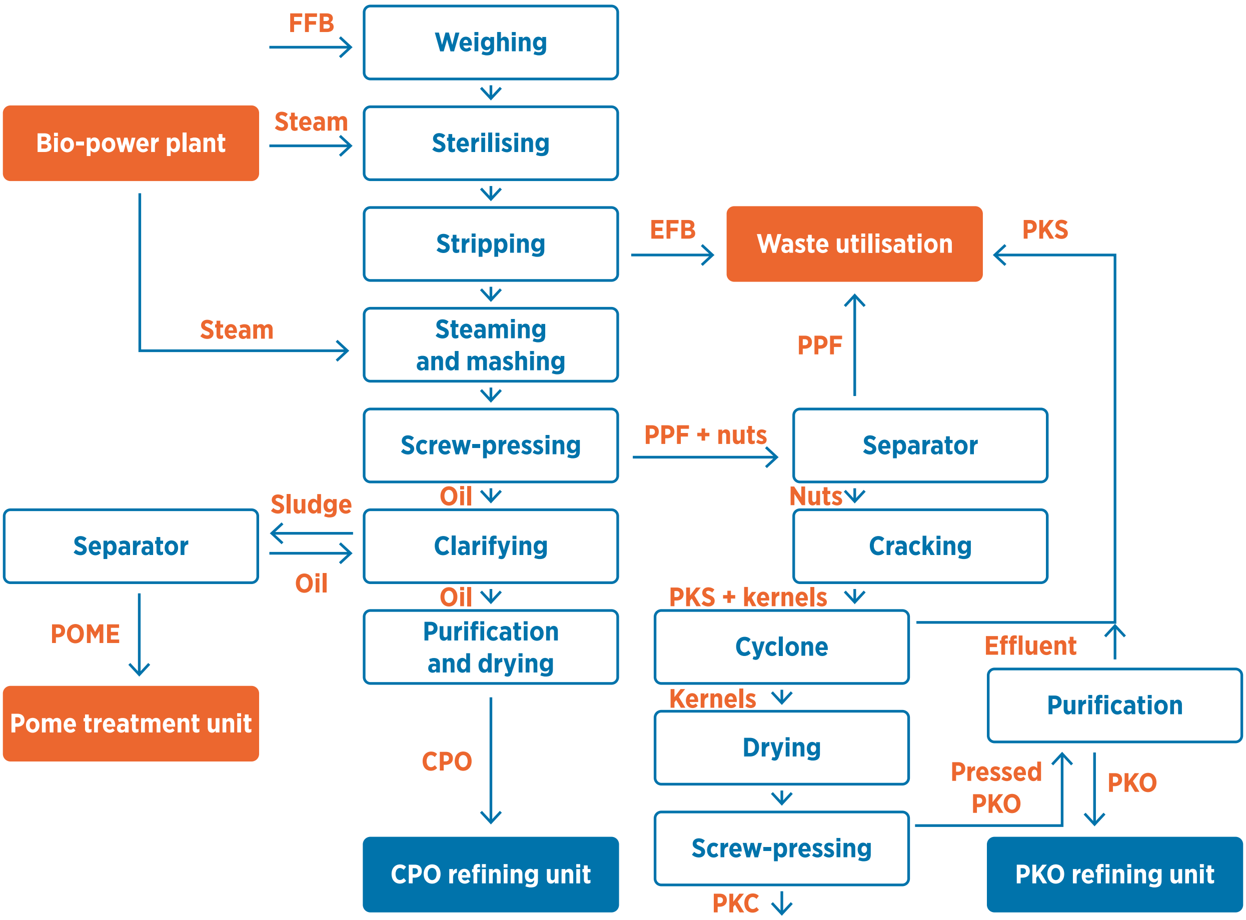
Based on: (FAO, 2023) data from the base year, 2019.
Note: kha = kilohectare; kt = kilotonne.

For oil palm, the fundamental approach to crop modelling is reductionist in nature: a relatively simple model should be able to predict the behaviour of complex crops. Nevertheless, the large number of processes and reactions involved in plant growth can quickly give rise to very complex models that, in principle, could not be tested and are unlikely to be valid beyond the environment in which they were developed. In the literature review work developed by (Woittiez *et al.*, 2017), the various research studies modelling oil palm productivity are synthesised, and it also points out the most important limiting factors (photosynthetically active radiation, temperature, ambient CO_2 concentration, water, nutrition and crop's genetic characteristics). Most importantly, all these heavily rely on the nature of the business models, especially scale, ranging from independent small farmers to large-scale industrial plantations.

2.4.2. Oil palm agro-industry: Crude palm oil and biodiesel production

Most commercial POMs typically process 3-60 tonnes of FFBs per hour (with an extraction efficiency of ~26% CPO per FFB), and they can process based on load or continuously depending on the FFB supply (Garcia-Nunez *et al.*, 2016a). Obtaining CPO from FFBs requires a series of processes, as shown in Figure 19. The initial stage involves sterilisation, where freshly harvested fruit bunches brought to the mill are subjected to high-pressure steam with a minimum delay to inactivate the lipolytic enzymes that cause the oil's hydrolysis and cause the fruit to deteriorate. The subsequent stage is known as bunch stripping. It involves separating the fruit from the stems of the bunch by mechanical de-leafing. The separated and sterilised fruit is then sent to a digestion process, where it is reheated using extraction steam at a temperature of no more than 90°C. In this manner, the fruits are prepared for oil extraction by breaking the oil-bearing cells in the mesocarp and loosening the mesocarp from the nuts. CPO is extracted from the digested fruit macerate by means of a screw press without breaking the kernel. Once extracted, the palm oil is clarified and purified.

Figure 19 Schematic diagram for a palm oil mill



Source: (Lee and Ofori-Boateng, 2013).

Note: CPO = crude palm oil; EFB = of empty fruit bunches; FFB = fresh fruit bunch; PKC = palm kernel cake; PKO = crude palm kernel oil; PKS = ; palm kernel shell; POME = palm oil mill effluent; PPF = palm pressed fibre.

The liquid and nuts obtained are discharged from the auger machine. The oil obtained contains water, solids and diluted impurities in different quantities, which must be eliminated. Fibre traces in the pressed crude oil are first filtered out by screening the oil through a vibrating sieve; sand and dirt are allowed to settle out. On the other hand, the water is removed by decantation or centrifugation, and, finally, by vacuum drying. It should be noted that the clarified crude oil still contains about 0.1-0.25% moisture (Mohammad *et al.*, 2021). This preserves oxidative properties and reduces the formation of soluble solids commonly called gums in trace quantities. The finished material is commercialised locally as CPO or can be refined further. The power for operating the equipment of a POM is mainly obtained from solid biomass such as EFBs, PKS and Palm-pressed fibre generated by the subprocesses, which are considered waste. Table 15 summarises the ranges of values that can be obtained from oil palm processing.

Before biodiesel production, crude palm oil has to be refined to reduce its acidity; *i.e.* the free fatty acids are eliminated, resulting in an oil that is composed of glycerides only. There are two distinct refining methods: chemical and physical (Figure 20). The physical method is the most used since it has a higher global yield, uses less chemicals and generates less effluents.

Finally, the refined oil is chemically processed to obtain biodiesel; the most used method for such processing is transesterification, which is carried out in the presence of an alcohol and an acidic or basic catalyst. Transesterification in industries commonly uses methanol as the alcohol, while sodium hydroxide is the preferred alkaline catalyst, due to its low cost. The conversion of palm oil via transesterification with methanol and alkaline catalysis offers the most interesting processing route, due to its fast reaction kinetics and a high rate of conversion of refined oil to biodiesel (methyl ester) at room temperature. Considerable crude glycerine production is nevertheless expected. The biodiesel thus produced is separated from the glycerol, washed in the first step with water and hydrochloric acid (pH 4.5) to neutralise the catalysts, centrifuged and dried to produce purified biodiesel; the average conversion efficiency is 97%. The glycerine can be commercialised after an additional purification process involving distillation (Lai *et al.*, 2012). Table 16 summarises the main operational parameters.

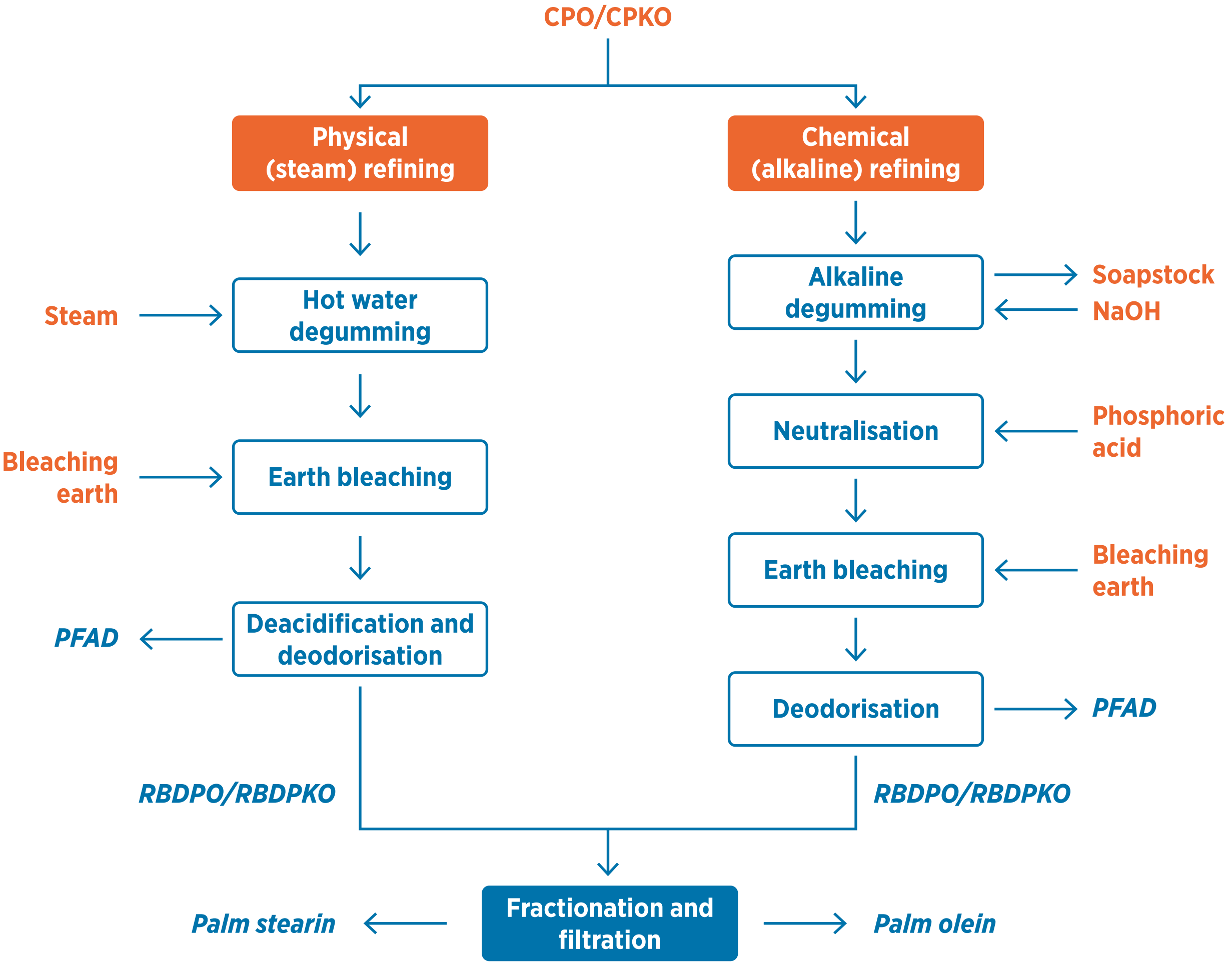
Table 15 Main parameters of the extraction stage of oil palm culture per tonne of FFB

OIL EXTRACTION	MEDIAN	MIN	MAX
Input			
Boiler water (kg)	534.29	307.40	761.18
Steam (kg)	1.03	0.82	1.27
Electricity (kWh)	104.30	1.89	206.73
Intermediate output			
Palm oil mill effluent (kg)	358.63	303.20	414.08
Fibre (kg)	130.00	82.59	177.41
Shell (kg)	55.00	34.93	75.06
Final output			
Crude palm oil (kg)	192.81	163.01	222.61
Empty fruit bunches (kg)	220.00	139.76	300.24
Biogas (Nm^3)	8.84	5.62	12.10

Sources: (Archer *et al.*, 2018; Garcia-Nunez *et al.*, 2016b; Lai *et al.*, 2012).

Note: FFB = fresh fruit bunch; kg = kilogramme; kWh = kilowatt hour; Nm^3 = normal cubic metre.

Figure 20 Flow chart for the principal refining methods



Source: (Lee *et al.*, 2013).

Note: CPO = crude palm oil; CPKO = crude palm kernel oil; NaOH = sodium hydroxide; PFAD = palm fatty acid distillate; RBDPO = refined, bleached and deodorised palm oil; RBDPKO = refined, bleached and deodorised palm kernel oil

Table 16 Main parameters of the refining and transesterification steps of palm oil biodiesel production

PARAMETER (INPUT/OUTPUT)	MEDIAN	MIN	MAX
Input			
Crude palm oil (kg)	987.90	835.20	1 140.60
Water (kg)	250.90	145.30	356.40
Electricity (kWh)	156.20	5.00	307.40
Methanol (kg)	136.80	93.20	180.50
Sodium hydroxide (kg)	6.00	2.00	10.00
Output			
Biodiesel (t)	1	1	1
Wastewater (kg)	250.90	145.30	356.40
Glycerol (kg)	156.30	102.60	210.00

Sources: (Archer *et al.*, 2018; Garcia-Nunez *et al.*, 2016; Lai *et al.*, 2012).

Note: kg = kilogramme; kWh = kilowatt hour; t = tonne.

2.4.3. Cogeneration from oil palm solid biomass

Like the sugarcane agro-industry, the oil palm agro-industry currently applies the concept of cogeneration. It uses as fuel the solid residues obtained from the palm oil extraction process. However, this is to meet the thermal energy demand for operating the industrial processes and to achieve electric self-sufficiency, not as a strategy to produce surplus power and sell it to the grid, as happens in the sugarcane industry. The biomass conventionally utilised for this form of generation is obtained from complete burning of fibre (about 13% of the total processed FFB) and part of the shell (about 7% of the total processed FFB).

Production of surplus electricity for sale requires adopting modern high-pressure boilers and extraction-condensation turbines that have efficiencies of at least 85% and generate a high amount of energy consuming less fuel (Julio *et al.*, 2021). According to data published by (Garcia-Nunez *et al.*, 2016a), the operational characteristics of cogeneration systems range from 5 MW to 40 MW. The steam parameters of such systems are 20/65 bar, with temperatures of 350/500°C, and the systems generate about 75-160 kilowatt hour per tonne (kWh/t) of FFB of excess electricity – a rate expected when the palm oil mill is operating or stopped, respectively (and about three or four times more than using a traditional back-pressure steam turbine system).

2.4.4. Electricity from palm oil mill effluent

Anaerobic digestion of palm oil mill effluent (POME) produces biogas in large quantities. It produces up to 28 cubic metres (m^3) of biogas per tonne of POME, equivalent to 18.2 m^3 of methane (CH_4) and 9.8 m^3 of CO_2 (Ohimain and Izah, 2017). The production of 1 tonne of crude palm oil therefore releases about 52 m^3 of methane emissions if considering the production of 210 kg of crude oil and the generation of 600 kg of POME per tonne of fresh fruit brought into the extraction plant (Aziz *et al.*, 2020). Over the past few years, it has become widespread in Southeast Asia to produce electricity from biogas produced in the treatment of POME (IRENA, 2022a). Each cubic metre of biogas can generate approximately 1.6 kWh, considering a lower heating value (LHV) of 22.90 megajoule (MJ)/m^3 and 25% efficiency. Latin American countries such as Peru, Honduras and Colombia have implemented clean production projects in oil extraction plants to capture the biogas produced in the POME treatment lagoons and generate electricity (Garcia-Nunez *et al.*, 2016a).

POME can be treated using multiple anaerobic digestion techniques; these include lagoon systems, upflow anaerobic digestion, anaerobic filtration, and anaerobic digesters and reactors of different configurations and designs. Global extraction plants widely use lagoons for POME treatment since they are cost-effective (Mohammad *et al.*, 2021).

2.5. SCENARIOS FOR OIL PALM BIOENERGY PRODUCTION

Like the sugarcane industry, the potential supply of biofuel and electricity from oil palm in the Caribbean SIDS was estimated for four scenarios. Such scenarios were analysed only for Caribbean countries that have the edaphic disposition and where the oil palm culture can be introduced and/or expanded; the Dominican Republic and Cuba were the cases for which these scenarios were analysed. First, two reference scenarios were developed, corresponding to palm oil extraction; these were denominated C0 (*Business as usual*) and C1 (*Business as usual with improved yield*). In both scenarios, the objective is to represent, as faithfully as possible, the most widespread technology in the Caribbean oil palm agro-industry, which consists of the use of traditional cogeneration plants with back pressure turbines to drive the generator and the mills.

In the improved scenarios, denominated C2 (*new framework – with minimum productivity*) and C3 (*new framework – with improved productivity*), corresponding to a palm biodiesel plant, bioenergy production (biofuel and bioelectricity) is prioritised. In both scenarios, the objective is to represent more efficient and mature technologies, which involve modern cogeneration plants (condensing/extraction steam turbine), use of all the fibre/shell and use of 50% of the EFB generated. It is important to note that scenarios C2 and C3 assumed the use of 25% and 40% of the area available for expansion in Cuba and the Dominican Republic, respectively. Table 17 summarises the main technological characteristics adopted by scenario.

2.5.1. Potential oil palm biodiesel supply

In scenarios C2 and C3, Cuba and the Dominican Republic could immediately displace, respectively, 26-43% and 11-17% of the overall diesel consumption using half of the potential CPO production as feedstock for biodiesel production. This would also produce interesting volumes for the global and/or national CPO, CPKO and glycerine markets – 50 000 to 892 000 tonnes of CPO, 6 500 to 228 000 tonnes of CPKO and 26 000 to 141 000 tonnes of glycerine annually (Table 18 & Figure 21).

Table 17 Description of the main parameters in the adopted scenarios

SCENARIOS	SUB-PLANTS	CHARACTERISTICS
C0	POM, conventional cogeneration plant, current yield	• Current productivity: 14 [t of FFB/ha.y] • CPO productivity: 180 [kg/t of FFB] • CPKO productivity: 23 [kg/t of FFB] • Steam consumption: 500 [kg/t of FFB] • Electricity surplus: 0 [kWh/t of FFB] • Mills powered by a steam turbine and a back pressure steam turbine
C1	POM, conventional cogeneration plant, improved yield	• Current productivity: 16 [t of FFB/ha.y] • CPO productivity: 180 [kg/t of FFB] • CPKO productivity: 23 [kg/t of FFB] • Steam consumption: 500 [kg/t of FFB] • Electricity surplus: 0 [kWh/t of FFB] • Mills powered by a steam turbine and a back pressure steam turbine
C2	Biodiesel plant from CPO, modern cogeneration plant, covered lagoon treatment and minimum yield	• Minimum productivity: 16.3 [t of FFB/ha.y] • CPO productivity: 180 [kg/t of FFB] • CPKO productivity: 23 [kg/t of FFB] • Steam consumption: 500 [kg/t of FFB] • Electricity surplus: 160 [kWh/t of FFB] • Biogas production: 15 [Nm^3/t of FFB] • Condensing/extraction steam turbine
C3	Biodiesel plant from CPO, modern cogeneration plant, covered lagoon treatment and improved yield	• Maximum productivity: 26.8 [t of FFB/ha.y] • CPO productivity: 180 [kg/t of FFB] • CPKO productivity: 23 [kg/t of FFB] • Steam consumption: 500 [kg/t of FFB] • Electricity surplus: 160 [kWh/t of FFB] • Biogas production: 15 [Nm^3/t of FFB] • Condensing/extraction steam turbine

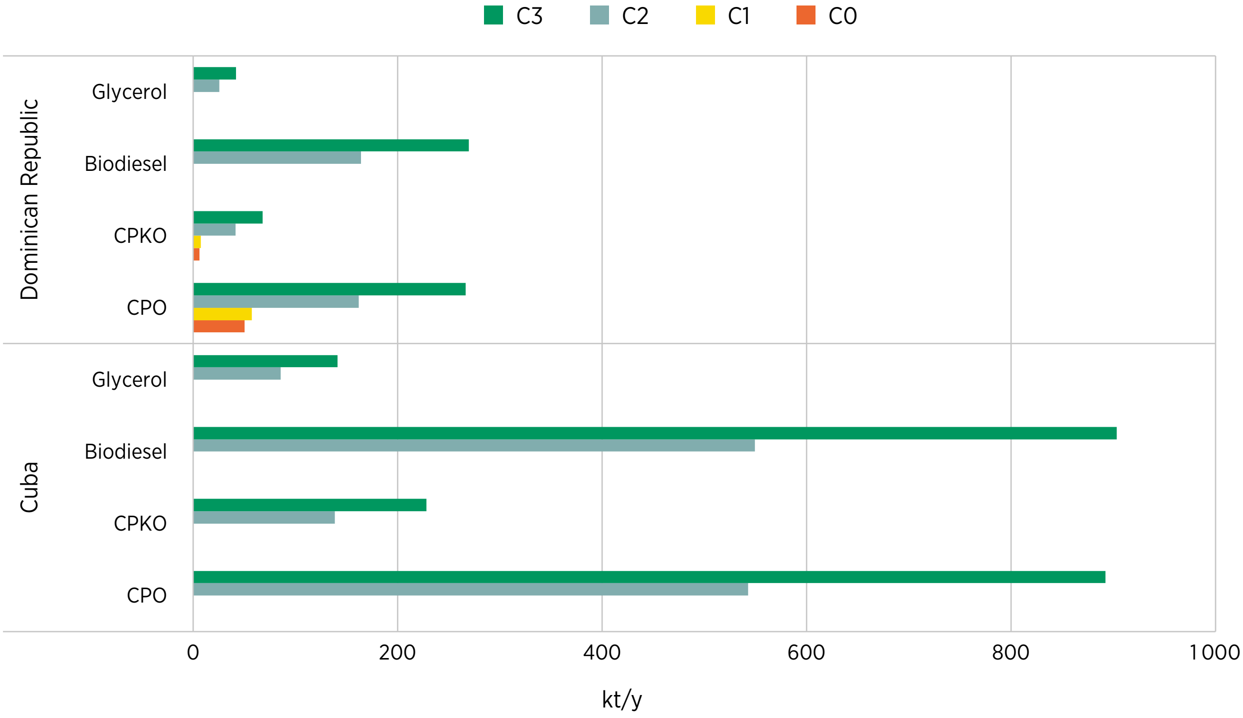
Note: C0 = business as usual; C1 = business as usual with improved sugarcane yield; C2 = new framework – without irrigation; C3 = new framework – with irrigation; CPO = crude palm oil; CPKO = crude palm kernel oil; FFB = fresh fruit bunch; ha.y = hectare per year; kg = kilogram; kWh = kilowatt-hour; Nm^3 = normal cubic metre; POM = palm oil mill; t = tonne.

Table 18 Potential oil-palm-based biodiesel supply in Cuba and the Dominican Republic (kt/year)

CARIBBEAN SIDS	PRODUCTS	C0 (kt/y)	C1 (kt/y)	C2 (kt/y)	C3 (kt/y)
Cuba	CPO	-	-	542.8	892.4
	CPKO	-	-	138.7	228.1
	Biodiesel	-	-	549.3	903.1
	Glycerol	-	-	85.9	141.2
Dominican Republic	CPO	50.5	57.6	162.2	266.7
	CPKO	6.5	7.4	41.4	68.1
	Biodiesel	-	-	164.1	269.9
	Glycerol	-	-	25.7	42.2

Note: C0 = business as usual; C1 = business as usual with improved sugarcane yield; C2 = new framework – without irrigation; C3 = new framework – with irrigation; CPO = crude palm oil; CPKO = crude palm kernel oil; kt = kilotonne; SIDS = small island developing states; y = year.

Figure 21 Potential biodiesel supply in the four scenarios



Note: C0 = business as usual; C1 = business as usual with improved sugarcane yield; C2 = new framework – without irrigation; C3 = new framework – with irrigation; CPO = crude palm oil; CPKO = crude palm kernel oil; kt/y = kilotonne per year.

2.5.2. Potential bioelectricity supply from oil palm by-products

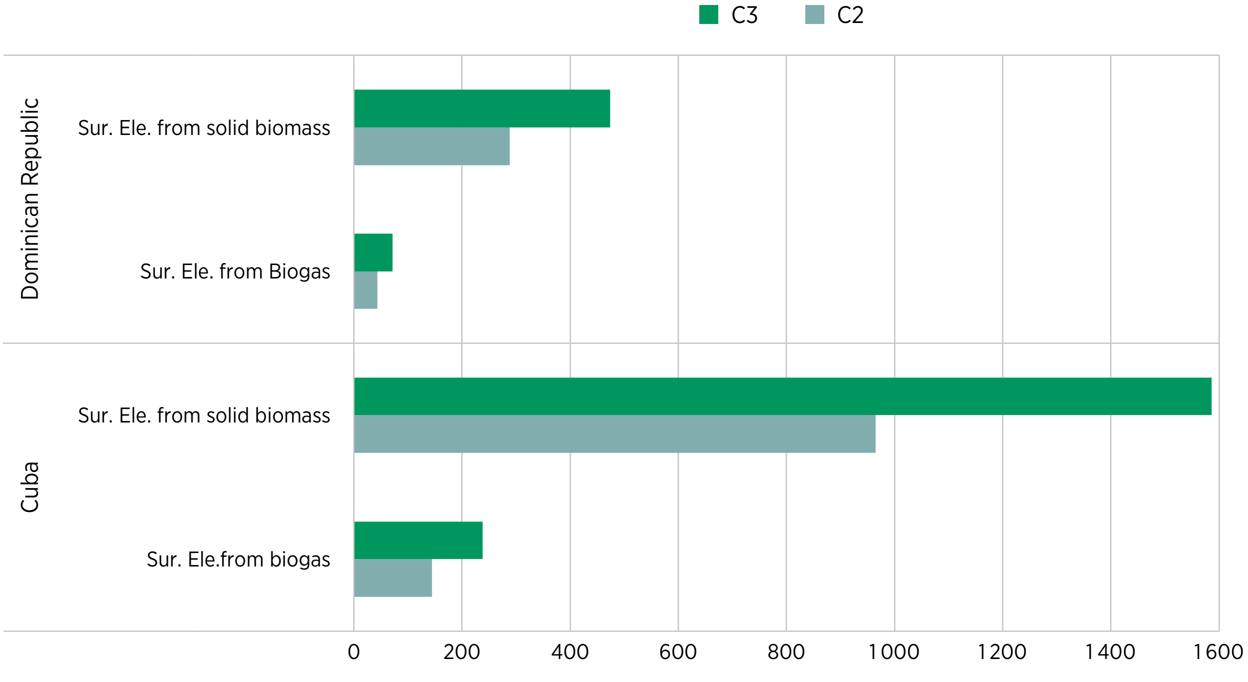
The utilisation of solid biomass from the palm process (fibre, shell and EFB) as a source of chemical energy in thermal power plants has a significant potential to increase power output and diversify the Dominican Republic's and Cuba's energy mix (Table 19 and Figure 22). Further, biogas production from liquid effluents could potentially account for a proportion of the countries' electricity consumption or natural gas consumption. Biogas production from liquid effluents could generate, respectively, 3.44-5.65 GWh and 2.90-4.76 GWh of electricity annually, and 36 200 to 59 500 m^3 and 29 300 to 48 100 m^3 of biogas annually in Cuba and the Dominican Republic. This should trigger a decrease in imports of foreign hydrocarbons for power generation and residential natural gas consumption, and improve the supply of these energies.

Table 19 Potential bioelectricity supply from biomass palm oil in Cuba and the Dominican Republic

CARIBBEAN SIDS	SURPLUS ELECTRICITY	C2 (GWh/y)	C3 (GWh/y)
Cuba	Biogas from POME	144.7	238.0
	Solid biomass (fibre, shell and EFB)	964.9	1 586.5
Dominican Republic	Biogas from POME	43.2	71.1
	Solid biomass (fibre, shell and EFB)	288.3	474.1

Note: C2 = new framework – without irrigation; C3 = new framework – with irrigation; EFB = empty fruit bunches; GWh = gigawatt hour per year; POME = palm oil mill effluent; SIDS = small island developing states.

Figure 22 Potential bioelectricity supply in the Dominican Republic and Cuba



Note: C2 = new framework – without irrigation; C3 = new framework – with irrigation; GWh = gigawatt hour; Sur. Ele. = surplus electricity.

Solid biomass from oil palm (fibre, shell and EFB) could represent, respectively, 12.1% and 3,5% of Cuba's and the Dominican Republic's overall electricity consumption if these countries use 25% and 40%, respectively, of the pastureland (under temporary or permanent use) to expand oil palm production. Like sugarcane, oil palm provides opportunities for these countries to reduce their heavy reliance on distillate fuel oil and natural gas for power generation. This would also increase the share of renewable energy from 2.6% and 1.2% to 5.9% and 4.2% for Cuba and the Dominican Republic, respectively.

2.6. THE BIOENERGY POTENTIAL OF MUNICIPAL SOLID WASTE

Since the last century, urbanisation and consumerism have grown worldwide; this has triggered a concerning increase in solid waste generation. In fact, MSW, which results from the growing annual waste generation, is a serious concern for both advanced and emerging economies. The increase in waste generation can be linked to economic progress, population growth and improved lifestyle, but it poses serious environmental and health hazards (Ilmas *et al.*, 2021). Under this view, the management (collection and disposal) of MSW is one of the key challenges facing most nations today. Alternatives to address such a concern must be environmentally friendly, legally – and socially – acceptable, technically feasible and economically affordable (Rodrigues *et al.*, 2022). The Caribbean SIDS face increasingly difficult challenges in managing solid waste; an aggravating aspect is that inappropriate solid waste management poses hazards to society and the environment, as is the case in the studied SIDS countries.

MSW is the type of waste typically produced by residential households, offices, businesses, hotels, schools and other institutional facilities. MSW mainly includes food waste, paper, plastics, metals, garden waste, cardboard and glass packaging waste. It may also contain demolition and construction debris and limited amounts of hazardous and chemical waste such as light bulbs, batteries, car parts, discarded medicines and chemicals (Hettiarachchi *et al.*, 2018).

The production of MSW is strongly correlated with community size and per capita income. The composition of this waste varies widely and depends on multiple factors, including socio-economic level, and cultural and geographic factors. Food waste typically constitutes about 25-35% (in weight) of MSW, paper about 25-35%, plastics about 7-10%, ferrous metals about 3-5%, non-ferrous metals about 0.5-2%, glass about 5-10%, yard waste about 10-15% and hazardous waste about 1-2% (Cayumil *et al.*, 2021). In low- and middle-income countries, organic waste constitutes over 50% of the total MSW produced. In high-income countries, this proportion is approximately 32%. Recoverable materials vary between 10% in low-income countries and up to 50% in high-income countries.

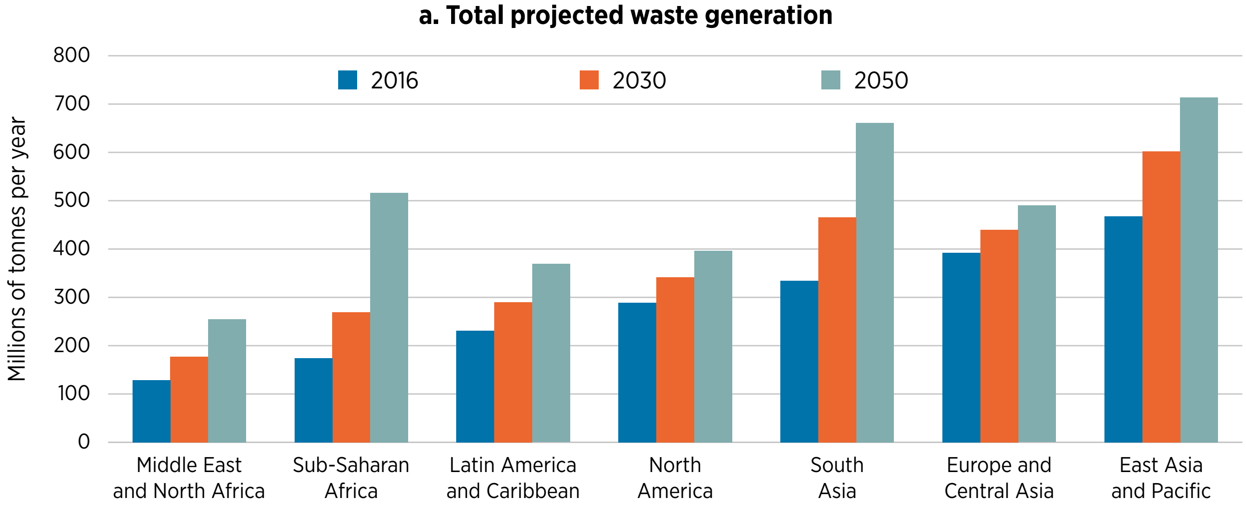
2.6.1. Waste generation and composition

Waste generation differs between economies. Developed countries (those with a GDP per capita above USD 10 000 per year, according to the International Monetary Fund) tend to have higher waste generation rates than less developed countries. Based on the 2018 World Bank report (*What a Waste 2.0*), 2.01 billion tonnes of MSW were generated globally in 2016, with the average waste generation rate being 740 grammes/capita/day (g/c/d) (Figure 23). The projected MSW production until 2050 stands at 3.4 billion tonnes per year (Kaza *et al.*, 2018). Waste generation in industrialised countries commonly ranges from 1 000 to 2 500 g/c/d, whereas emerging countries typically have waste generation rates ranging from 500 to 1 000 g/c/d (Kumar and Samadder, 2017).

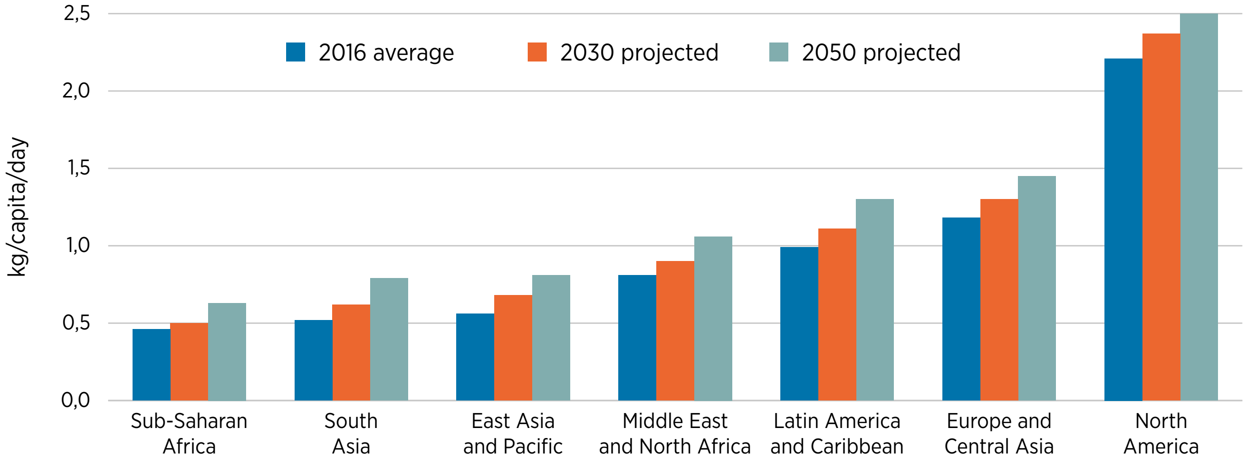
A total of 231 Mt of waste were generated in the Latin America and the Caribbean in 2016; per capita values ranged from 0.41 to 4.46 kilogrammes/capita/day (kg/c/d), with an average of 0.99 kg/c/d. Note that the nations with the steepest per capita indices are islands (Figure 24), probably due to waste generated by the tourism industry (Hettiarachchi *et al.*, 2018) also because their accounting of all wastes generated may be more thorough than that of larger states. For the Caribbean SIDS specifically, per capita values vary between 0.58 and 1.52 kg/c/d, with an average of 1.05 kg/c/d (Kaza *et al.*, 2018). Based on these figures, Table 20 presents the estimated total MSW generation for 2021, considering the total urban population and its total MSW generation rate.

Apart from waste production, waste characterisation is an essential aspect in formulating appropriate waste management strategies. It is feasible to identify the recyclability, combustibility or biodegradability of waste streams based on waste concentration parameters. These can then be used to design and implement suitable waste management technologies. Meanwhile, the approach for Caribbean countries is entirely different from that for developed countries; solid waste contains nearly 50% water, which permeates certain recyclables, for example, cardboard and paper, reducing the possibilities to recycle them (Table 21).

Figure 23 Projected waste generation by region



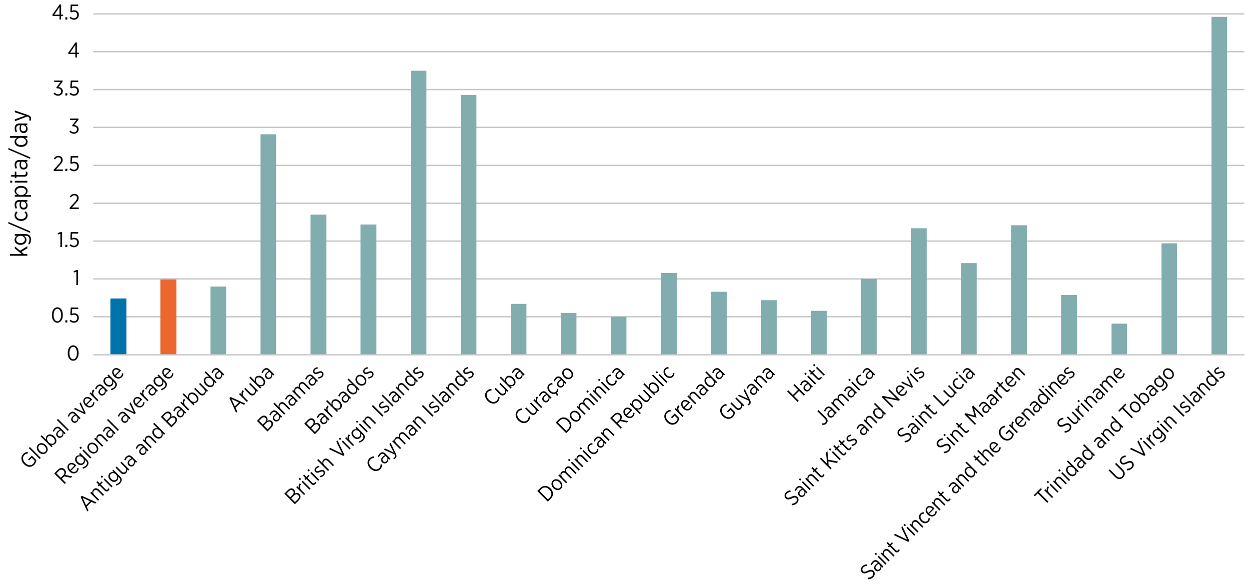
b. Projected waste generation per capita



Source: (Kaza *et al.*, 2018).

Note: kg = kilogramme.

Figure 24 Waste generation rates in Latin American and the Caribbean



Source: (Kaza *et al.*, 2018).

Note: kg = kilogramme.

Table 20 MSW generation by Caribbean country – current data

CARIBBEAN SIDS	INCOME LEVEL	TOTAL URBAN POPULATION, 2021[a] [1 000 PERSONS]	MSW GENERATION RATE[b] [kg/c/d]	TOTAL MSW GENERATION, 2021 [Mt/year]
Guyana	LMI	208.91	1.52	115.91
Cuba	UMI	8 739.13	0.67	2 137.16
Dominican Republic	UMI	8 787.47	1.08	3 464.02
Haiti	LI	6 328.94	0.58	1 339.84
Jamaica	UMI	1 650.59	1.00	602.47
Trinidad and Tobago	HI	741.94	1.47	398.09

Sources: [a](World Bank, 2022); [b](Kaza *et al.*, 2018).

Note: HI = high income; kg/c/d = kilogrammes/capita/day; LI = low income; LMI = low and middle income; MSW = municipal solid waste; Mt = million tonne; SIDS = small island developing states; UMI = upper and middle income.

Table 21 Typical MSW composition by Caribbean country

CARIBBEAN SIDS	CONSTITUENTS OF MSW (%)					
	ORGANICS	PAPER/CARDBOARD	PLASTICS	GLASS	METALS	OTHERS
Guyana[a]	50.00	10.00	19.00	5.00	4.00	12.00
Cuba[b]	62.00	12.00	9.00	10.00	2.00	5.00
Dominican Republic[c]	53.50	17.00	8.40	3.80	1.70	15.60
Haiti[d]	75.00	3.00	7.00	2.00	3.00	10.00
Jamaica[d]	62.20	14.70	12.20	2.80	2.40	5.70
Trinidad and Tobago[d]	26.70	19.70	19.90	10.50	10.4	12.60

Sources: [a](Mohee *et al.*, 2015); [b] (Lorenzo Llanes and Kalogirou, 2019); [c](Margallo *et al.*, 2019); [d](Hoornweg and Bhada-Tata, 2012).

Note: MSW = municipal solid waste; SIDS = small island developing states.

Appropriate final disposal of MSW is a serious challenge in the Caribbean SIDS: only a few countries dispose of their MSW in sanitary landfills; in most cases, MSW is disposed of in open-air landfills, which is the predominant mechanism (~ 80%) but causes extensive damage to the environment (Riquelme and Méndez, 2016). In most Caribbean states, final disposal locations are managed by a public entity. In a few cases, such as the Dominican Republic and Trinidad and Tobago, private sector participation has been observed.

One important parameter of MSW is its heating value (HV) or calorific value (CV). Although data for these are not typically available, these constitute essential information to effectively design and successfully operate and maintain a waste-to-energy (WtE) facility (Tchobanoglous and Kreith, 2002). A crucial shortcoming is the divergent information on the energy values of MSW. In general, published works describe energy content in terms of higher heating value (HHV), lower heating value (LHV), CV, net CV and gross CV (Margallo *et al.*, 2019). The equation typically applied in the theoretical estimation of solid fuels' CVs is the Dulong equation, which was originally developed for estimating the CV of coal and may not be applicable for estimating MSW's CV. LHV calculation is based on the feedstock's HHV and moisture content (Yi *et al.*, 2018). LHV has more practical applications than HHV, and it is widely adopted in energy assessment, since this is the energy that is utilised in power generation via WtE routes. Table 22 shows the typical LHVs of MSW's constituents.

Table 22 Typical LHVs of MSW's constituents

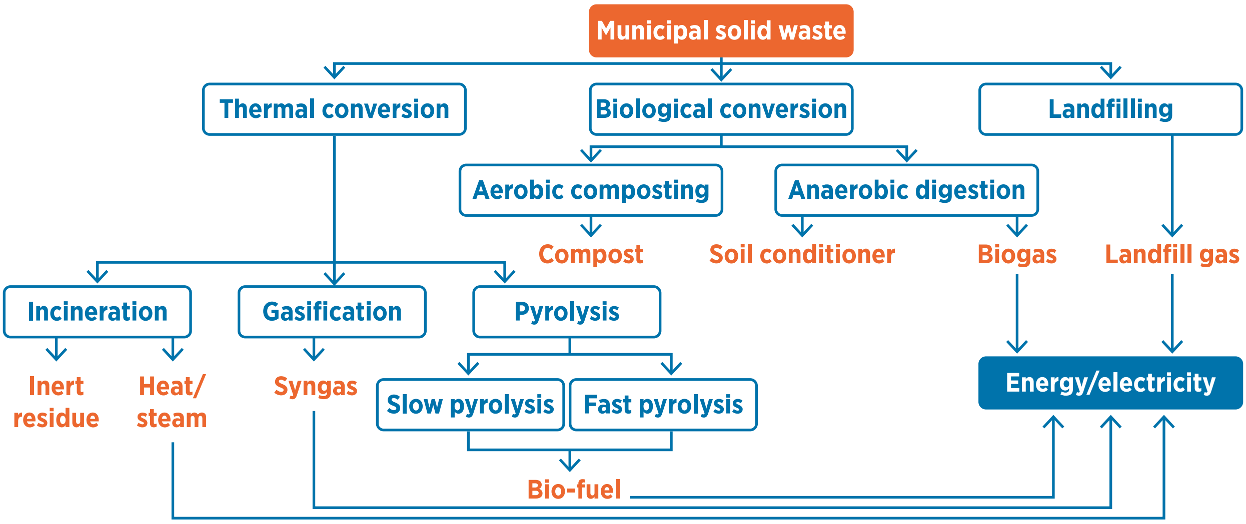
COMPONENT	ENERGY [kJ/kg]	
	RANGE	TYPICAL
Food waste	3 489-6 978	4 652
Paper	11 630-18 608	16 747
Cardboard	13 956-17 445	16 282
Plastics	27 912-37 216	32 564
Textiles	15 119-18 608	17 445
Rubber	20 934-27 912	23 260
Leather	15 119-19 771	17 445
Garden trimmings	2 326-18 608	6 513
Wood	17 445-19 771	18 608
Glass	116.3-232.6	139.5
Tin cans	232.6-1 163	698
Ferrous metals	232.6-1 163	698
Dirt, ashes, brick, etc.	2 326-1 160	6 978

Source: (Tchobanoglous *et al.*, 2002).
Note: kj/kg = kilojoule per kilogramme.

2.7. WASTE-TO-ENERGY PATHWAYS

Waste treatment and transformation systems are primarily for recovering energy and material, and then waste disposal. Yet, the choice of a waste treatment and transformation technology depends not only on economic considerations, energy recuperation or waste reduction capacity, but also on compliance with environmental regulations. The most appropriate technological option for waste treatment is thus one that meets the criteria for successful operation, which complies with environmental regulations (Malinauskaite *et al.*, 2017).

Figure 25 MSW treatment techniques and their products



Source: (Kumar *et al.*, 2017).

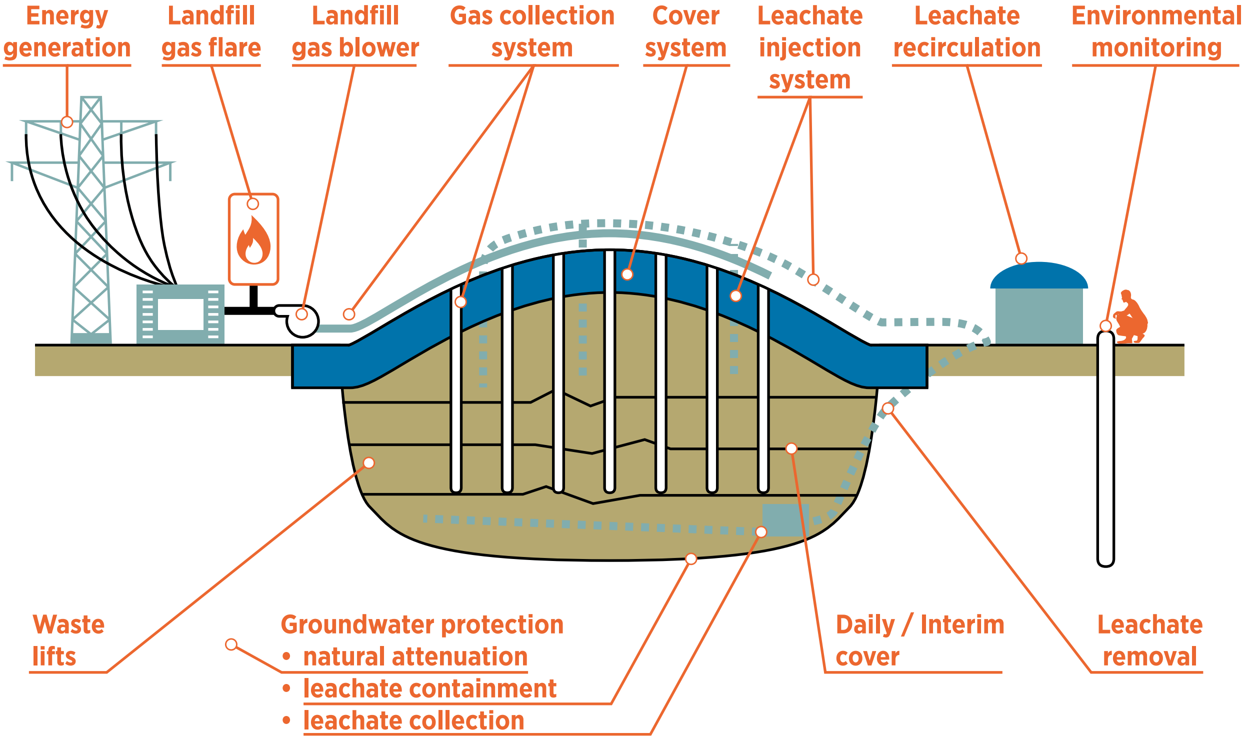
There are several processes to convert residue, although the three most commonly employed technological alternatives are (1) the thermochemical route (direct burning, pyrolysis, gasification, production of energy from refuse-derived fuel); (2) the biochemical route (anaerobic digestion and composting); and (3) LFG to energy. Figure 25 presents MSW treatment alternatives and the standard reaction products.

Given the highly organic nature of the waste in the Caribbean SIDS, as shown in Table 21, there exists potential for recuperation; for example, LFG capture and anaerobic digestion appear to be the two technological options most conducive to MSW management in the region. As for the constituents with the second-largest share (recyclables), these can be recycled or combusted (Silva-Martínez *et al.*, 2020).

In the Caribbean SIDS, it is common for MSW to be disposed of in landfills and at dumpsites, due to its low-cost management procedure. However, in most cases, these landfills lack leachate treatment, and LFG treatment and recovery; this generates a considerable environmental impact when compared with other alternative waste treatment methods (Margallo *et al.*, 2019). A sanitary landfill, as opposed to controlled landfills and open dumps, is understood as a process of controlled degradation of waste on land so as to mitigate adverse environmental impacts through biogas capture and appropriate leachate disposal (Figure 26).

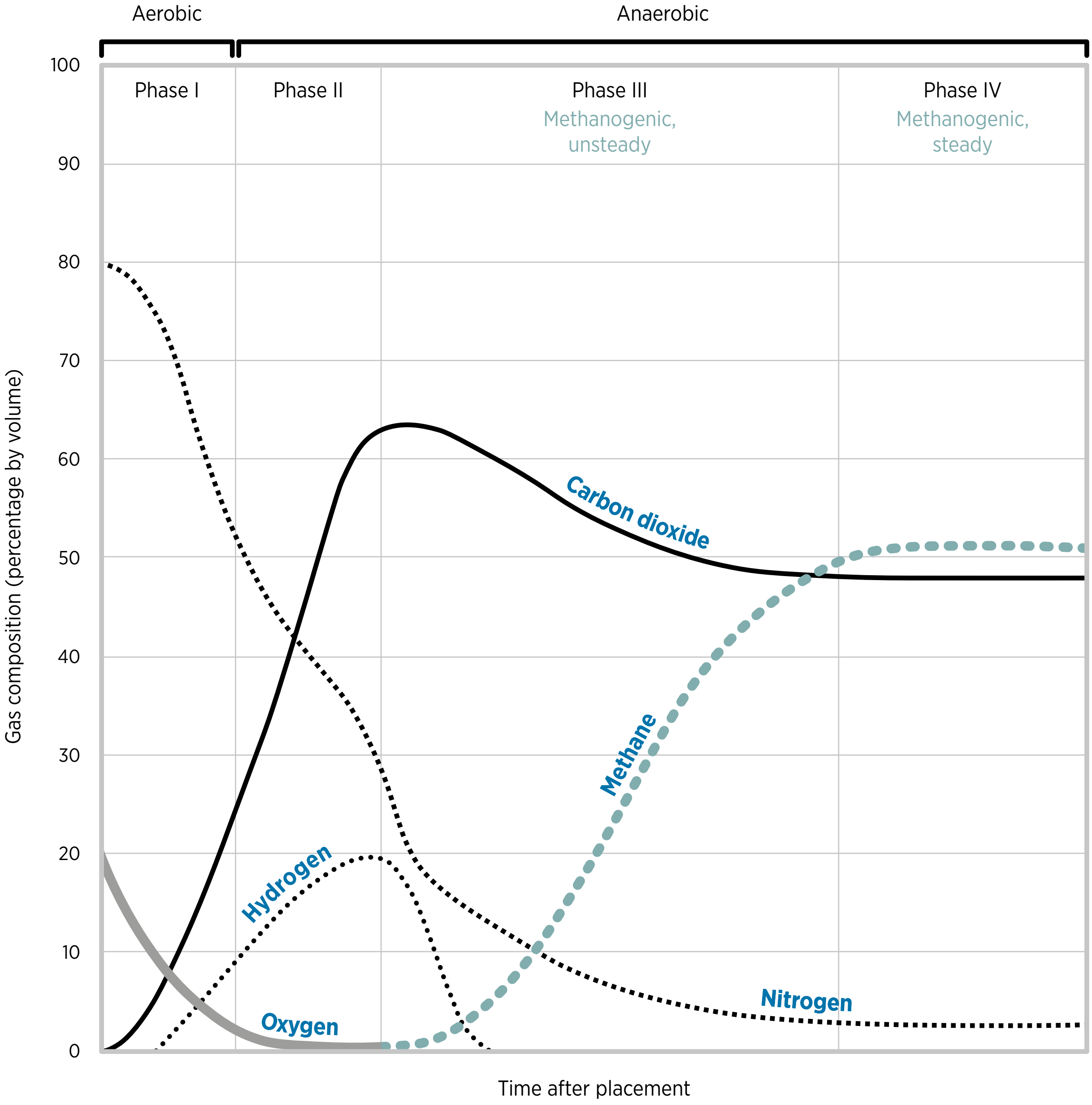
The organic matter contained in the waste deposited in a landfill undergoes complex biological and chemical degradation, which results in the production of LFG. The organic matter in LFG decomposes in five distinct phases: (1) hydrolysis/aerobic degradation, (2) hydrolysis and fermentation, (3) acidogenesis/acetogenesis, (4) methanogenesis and (5) oxidation (Figure 27). The rate of LFG production in a landfill is linked to several factors, for example, the landfill's class, the waste's volumetric composition, climatic characteristics, water content and the time for the waste to decompose (Silva-Martínez *et al.*, 2020). LFG contains 50-60% methane (Pan *et al.*, 2018), and is considered one of the major sources of anthropogenic methane emissions. According to the US Environmental Protection Agency (EPA, 2022), landfills are estimated to emit just under 70 Mt of biomethane gas per year. Thus, the collection of biomethane from a landfill for power generation or another application is necessary to limit emissions. LFG generally undergoes an exothermic chemical reaction in situ if its recovery is not technologically feasible.

Figure 26 A standard landfill with a biogas collection system



Source: (Kumar *et al.*, 2017).

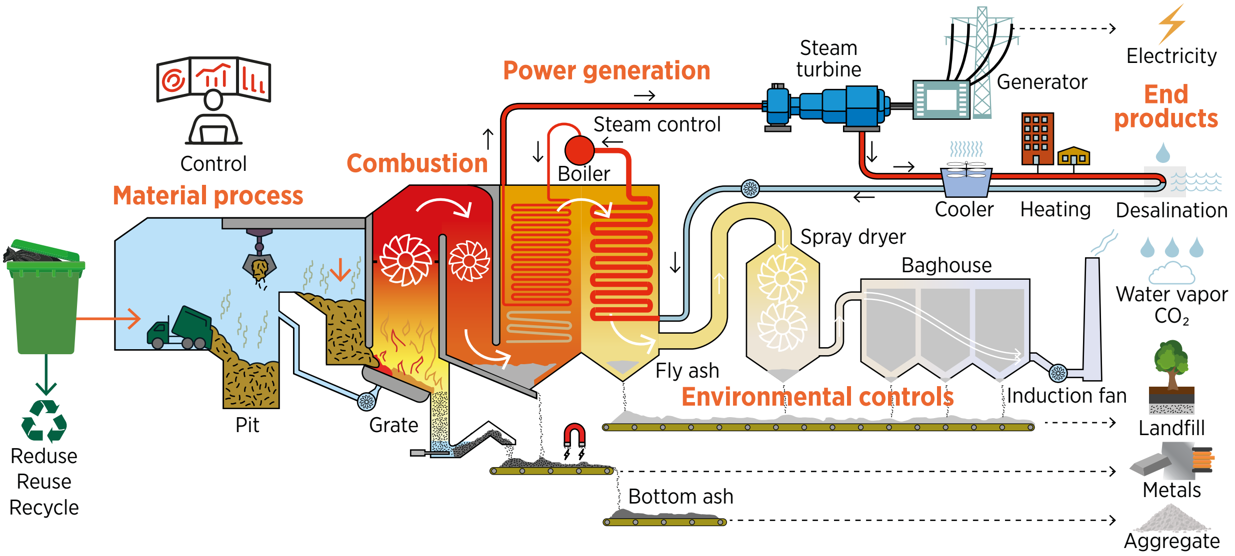
Figure 27 Production phases for typical landfill gas



Source: (EPA, 2022).

Several technologies have been used to produce power from LFG; examples include power cycles, reciprocating internal combustion engines, the Brayton cycle (gas turbines and micro-turbines) and gradual oxidation (GO). Reciprocating engines are the most widely used technology for power generation from LFG. While reciprocating internal combustion engines have low capital cost and can easily start up and reach full load, which are their essential advantages, their operational availability is lower than that of other technologies. Reciprocating engines can achieve 25-40% electric energy generation efficiency, with operational availability of about 85%, and may operate at biomethane concentrations of over 40% in the LFG. Also, they only require relevant operating and maintenance costs, which are generated approximately every seven years of continuous operation (Manasaki *et al.*, 2021).

Figure 28 A typical MSW direct combustion (incineration) plant



Source: (EIA, 2022b)
Note: CO_2 = carbon dioxide; MSW = municipal solid waste.

Some studies (Collivignarelli *et al.*, 2017; Lino and Ismail, 2017; Wang *et al.*, 2019) have highlighted other benefits of direct combustion, besides volume reduction and power generation. An example of those benefits is the utilisation of bottom and fly ash from incineration plants in road construction, cement production and the recuperation of ferrous and non-ferrous substances (Figure 28). In such a manner, further technological advancement in metal recovery from the dry bottom ash of incineration plants will increase acceptance for WtE facilities (Makarichi *et al.*, 2018). However, in developing nations, incineration is regarded as the most efficient and economical technology when applied for mass combustion without pretreatment of MSW for power generation. Direct combustion is carried out in multiple stages, which are directly influenced by the operating conditions and the residues' physicochemical characteristics (Sakai and Hiraoka, 2000). A main peculiarity of MSW incineration is the complete degradation of organic materials and the mineralisation of organic substances into innocuous end substances (Kumar *et al.*, 2017). A standard incinerator generates 0.5 megawatt hours of energy from 0.2 tonnes of solid waste for each tonne of MSW incinerated (Makarichi *et al.*, 2018). Incineration has several disadvantages; for example, its installation and operating costs are high, due to the requirement of advanced environmental control systems in terms of dioxin emissions and the generation of solid particles and metal-rich residues during combustion (Makarichi *et al.*, 2018).

2.8. SCENARIOS FOR ENERGY PRODUCTION FROM MUNICIPAL SOLID WASTE

Considering the information presented previously and with the aim of promoting the appropriate processing and adequate disposal of solid waste, and power recovery from them in the Caribbean SIDS, the waste-to-energy-recovery potential was evaluated considering two MSW management scenarios: (1) sanitary landfills and (2) direct combustion (incineration). Initially, the MSW index and population for each Caribbean SIDS nation were obtained. Subsequently, based on the data obtained, the volume of waste generated annually in each country (V_{MSV}), was calculated using Eq. (2):

$$V_{MSW} = I \bullet T_{UP} \bullet MSW_{CE} \bullet 365 \tag{2}$$

In the equation, V_{MSV} is the volume of waste generated in each country (kg/y), I is the MSW generation index (in kg/c/d), T_{UP} is the number of inhabitants generating solid waste in a country and MSW_{CE} is the MSW collection efficiency (Table 23).

Table 23 Municipal solid waste and landfill gas collection efficiency

CARIBBEAN SIDS	GUYANA	CUBA	DOMINICAN REPUBLIC	HAITI	JAMAICA	TRINIDAD AND TOBAGO
MSW_{CE}	89%	76%	69%	11%	62%	100%
F	63%	95.2%	60%	76%	100%	94%

Source: (Kaza *et al.*, 2018).

Note: CE = collection efficiency; F = landfill gas collection efficiency; MSW = municipal solid waste; SIDS = small island developing states.

The total volume of MSW deposited in landfills (V_L) was obtained using Eq. 3, based on the volume of solid waste generated in each country and the organic fraction of the solid waste disposed of in landfills in each of them (F) (Table 21):

$$V_L = V_{MSW} \bullet F \tag{3}$$

The total annual biogas production in each country was estimated by adopting the average specific biogas generation factor for urban solid waste, 170 m^3/t (Conestoga-Rovers & Associates, 2004), the total MSW deposited annually in landfills (Eq. [3]) and the LFG recovery efficiency (assumed to be 50%) (EIA, 2022a). The energy available in the produced biogas can be computed based on its low heating value, 22 MJ/m^3 (EIA, 2022a).

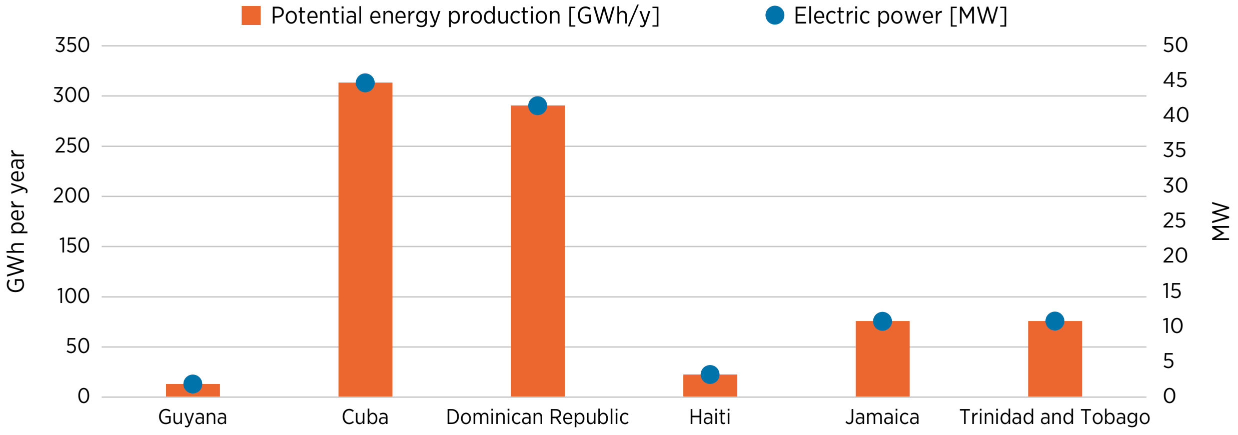
For the direct burning technology, the energy available in the MSW to be burnt was evaluated by estimating its average heating value, considering the gravimetric composition of MSW in each country (Table 21), the heating value of MSW's constituents (Table 22) and the total MSW collected (Eq. 2). In this study, wet heating values were adopted since MSW drying was not considered.

It was possible to eventually compute the electrical energy that can be generated annually and, adopting an 80% capacity factor (Lino *et al.*, 2017), estimate the power capacity that can potentially be installed. These could be computed based on the chemical energy available in the biogas and that derived from MSW direct burning, considering the power plant conversion efficiency. For biogas, 33% efficiency was assumed for use in internal combustion motors (Manasaki *et al.*, 2021) and 22% efficiency was assumed for direct burning of MSW in a conventional Rankine cycle (Makarichi *et al.*, 2018).

2.8.1. Potential of sanitary landfills

Figure 29 presents the estimated electricity and power capacity potential for the use of MSW by anaerobic digestion for the studied Caribbean countries.

Figure 29 Potential power available for biogas generated from landfills in several Caribbean nations



Note: GWh/y = gigawatt hour per year; MW = megawatt.

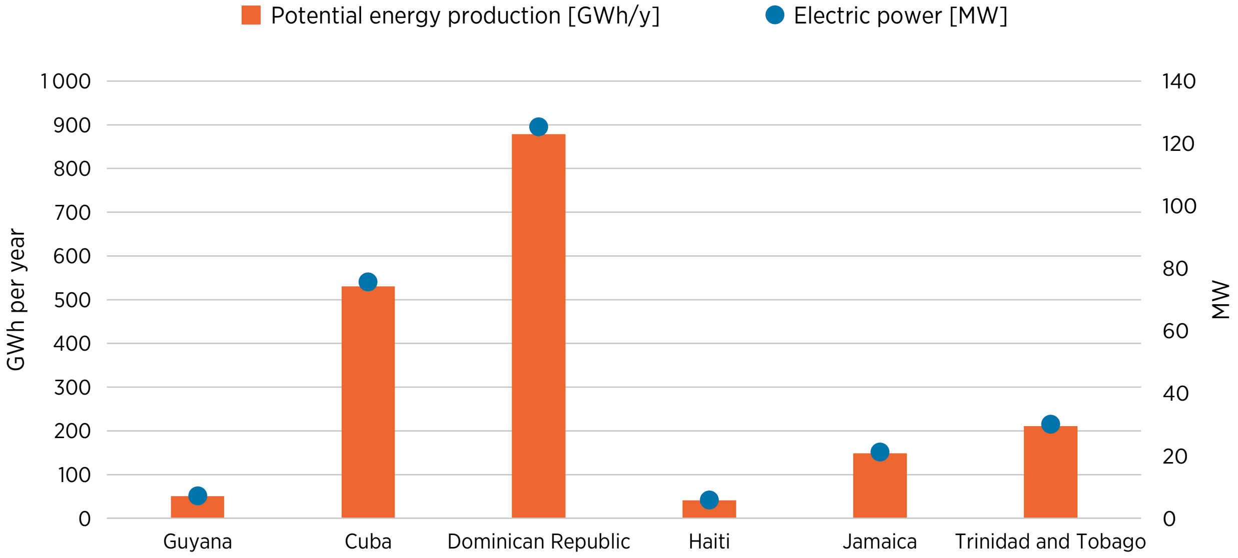
Energy potential considering LFG is the highest in the most populous Caribbean islands with the highest solid waste generation: Cuba (over 313 GWh/y) and the Dominican Republic (over 290 GWh/y). The other countries studied – Guyana, Haiti, Jamaica and Trinidad and Tobago – present lower potential and are able to supply, respectively, 1.46%, 7.57%, 2.44% and 0.93% of their individual electricity consumption.

2.8.2. Potential of the direct combustion (incineration) process

As indicated in Figure 30, potential energy production from MSW's direct combustion increased substantially in all studied Caribbean countries compared with potential energy production from biogas. The Dominican Republic stands out, with over 878 GWh of energy produced per year, due to its MSW mass flow and energy quality (7.5 MJ/kg). It is followed by Cuba (over 530 GWh/y), Trinidad and Tobago (211 GWh/y), Jamaica (148 GWh/y) and Haiti (41 GWh/y).

Although this scenario corresponds to the highest electricity generation, since it is a direct exothermic reaction of waste, without intermediate transformation (such as anaerobic digestion), it must be pursued cautiously, since there is a possibility of atmospheric pollution by dioxin and furan emissions if these are not strictly controlled.

Figure 30 Potential energy available for incineration in various Caribbean countries



Note: GWh/y = gigawatt hour per year; MW = megawatt.

3. ENVIRONMENTAL, SOCIAL AND ECONOMIC IMPACTS

When exploring policies to promote sustainable bioenergy, decision makers should not only assess how much energy can be produced sustainably, but also the expected environmental and socio-economic impacts related to such production. Based on the preceding analysis, this section assesses, for the selected Caribbean SIDS, the potential impact on greenhouse gas (GHG) emissions, evaluated as emissions of carbon dioxide equivalents (CO_2eq); the potential employment generation; and the economic investments and costs associated with the deployment of sugarcane, oil palm and MSW feedstock-based liquid biofuel and bioelectricity production chains.

The C0 and C3 scenarios were considered for the assessment; one is near current conditions and the other considers improvements. For bioelectricity, the scenarios with the greatest bioelectricity production potential were selected, with the objective of partially and/or fully supplying the electricity demand.

Table 24 summarises key outcomes for selected environmental, social and economic indicators. This highlights the relevance of modern bioenergy as a strategic option for sustainable development in the selected Caribbean SIDS.

Table 24 Summary of environmental, social and economic impact indicators of modern bioenergy development in selected Caribbean SIDS

CARIBBEAN SIDS	KEY FINDINGS		
	DECARBONISATION IMPACT (TOTAL GHG EMISSION MITIGATION)	POTENTIAL JOBS GENERATION (DIRECT, INDIRECT AND INDUCED)	ECONOMIC IMPACT* (ANNUAL COST OF INVESTMENT REQUIRED)
Cuba	0.48 to 15.9 $MtCO_2/y$	204+ million jobs	USD 335 million to USD 508 million
Dominican Republic	0.1 to 5.8 $MtCO_2/y$	38+ million jobs	USD 51 million to USD 77 million
Guyana	28 to 1 462 $ktCO_2/y$	15+ million jobs	USD 21 million to USD 32 million
Haiti	44 to 1 103 $ktCO_2/y$	41+ million jobs	USD 55 million to USD 84 million
Jamaica	20.9 to 923 $ktCO_2/y$	5+ million jobs	USD 6.4 million to USD 9.7 million
Trinidad and Tobago	0 to 402.3 $ktCO_2/y$	1.6+ million jobs	USD 4 million to USD 6 million

*The annual cost of investment was evaluated for two financing scenarios: (1) lower: 8% interest rate and a 15-year amortisation period, and (2) higher: 12% interest rate and a 10-year amortisation period.

Note: GHG = greenhouse gas; tCO_2 = tonnes of carbon dioxide; SIDS = small island developing states.

3.1. DECARBONISATION

Deployment of sustainable bioenergy systems has one positive environmental impact: it helps mitigate GHG emissions of national energy systems. The GHG emission factors adopted in this report come from life cycle analysis studies developed in the Latin American and Caribbean region – specifically, from the tropical and subtropical countries (such as Cuba, Colombia, Mexico and Brazil), which have similar edaphoclimatic characteristics. The life cycle analyses of (Cortez *et al.*, 2018; García *et al.*, 2011; Julio *et al.*, 2022; Pereira *et al.*, 2018) yielded average emission factors of, respectively, 0.5 tCO_2eq/m^3 and 0.61 tCO_2eq/m^3 for sugarcane ethanol and palm biodiesel. On the other hand, studies by (Carvalho *et al.*, 2019; Lorenzo Llanes *et al.*, 2019; Ocampo Batlle *et al.*, 2020) analysed carbon emission due to electricity production from the combustion of biomass from sugarcane (bagasse and straw), palm (fibre, shell and EFB), biogas and MSW, and obtained average factors of, respectively, 0.23, 0.19, 5.41 and 1.50 $kgCO_2eq/kWh$.

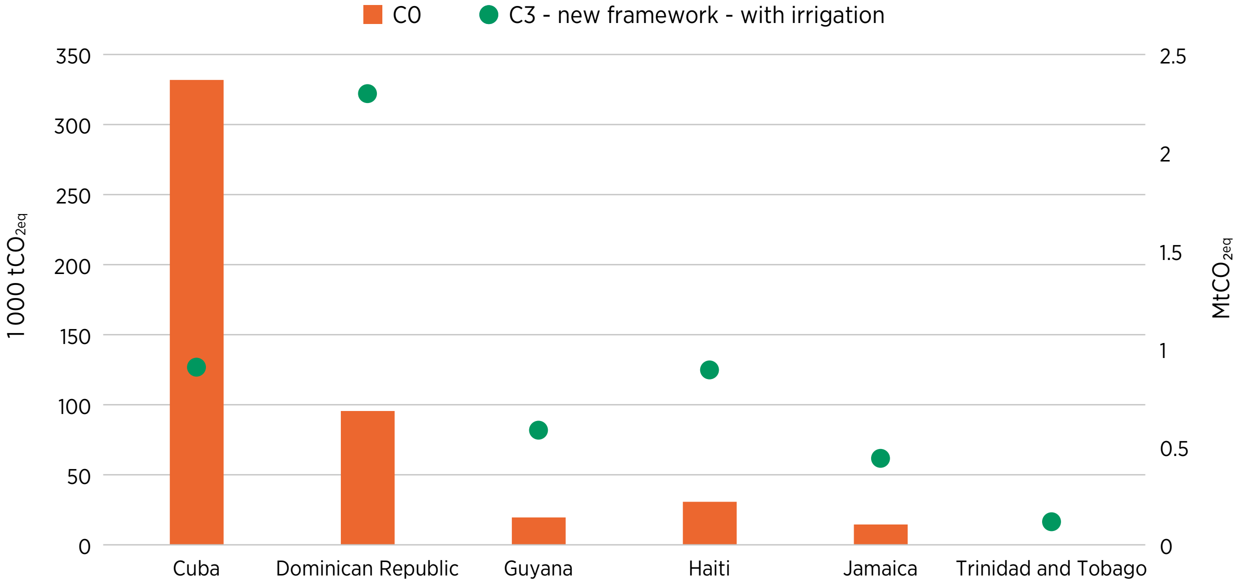
Table 25 and Figures 31 and 32 summarise potential CO_2 emissions avoided due to the displacement of diesel and gasoline by bioethanol and biodiesel in the selected Caribbean SIDS. As expected, this impact depends on fleet size, gasoline/diesel demand and the availability of ethanol/biodiesel.

Table 25 CO_2 emissions avoided due to the displacement of gasoline by sugarcane ethanol for scenarios C0 and C3

CARIBBEAN SIDS	C0 – BUSINESS AS USUAL (THOUSAND tCO_2eq)	C3 – NEW FRAMEWORK – WITH IRRIGATION (MILLION tCO_2eq)
Guyana	19.6	0.58
Cuba	332	0.91
Dominican Republic	95.6	2.30
Haiti	30.7	0.89
Jamaica	14.5	0.44
Trinidad and Tobago	-	0.12

Note: tCO_2eq = tonnes of carbon dioxide equivalent; SIDS = small island developing states.

Figure 31 CO_2 emissions avoided due to the displacement of gasoline by sugarcane ethanol for scenarios C0 (left axis) and C3 (right axis)

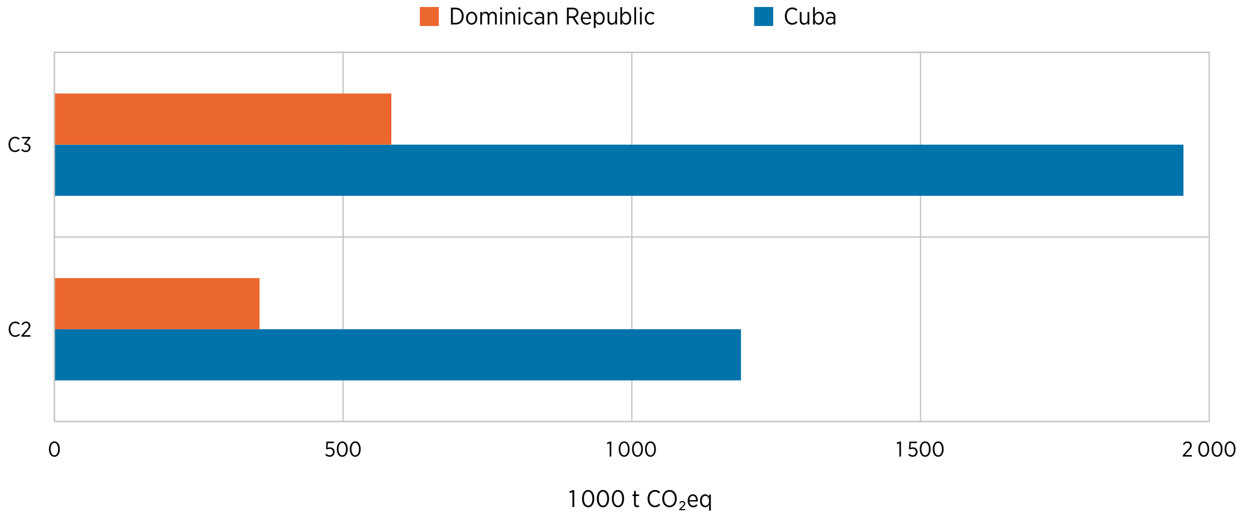


Note: $MtCO_2eq$ = million tonnes of carbon dioxide equivalent.

On the other hand, substitution of fossil diesel by palm oil biodiesel would generate CO_2eq reduction in the order of, respectively, 1.2 million and 355 200 tCO_2eq/y in scenario C2 for Cuba and the Dominican Republic. As for C3, such reductions would increase by about 64%, due to technical improvements in the system.

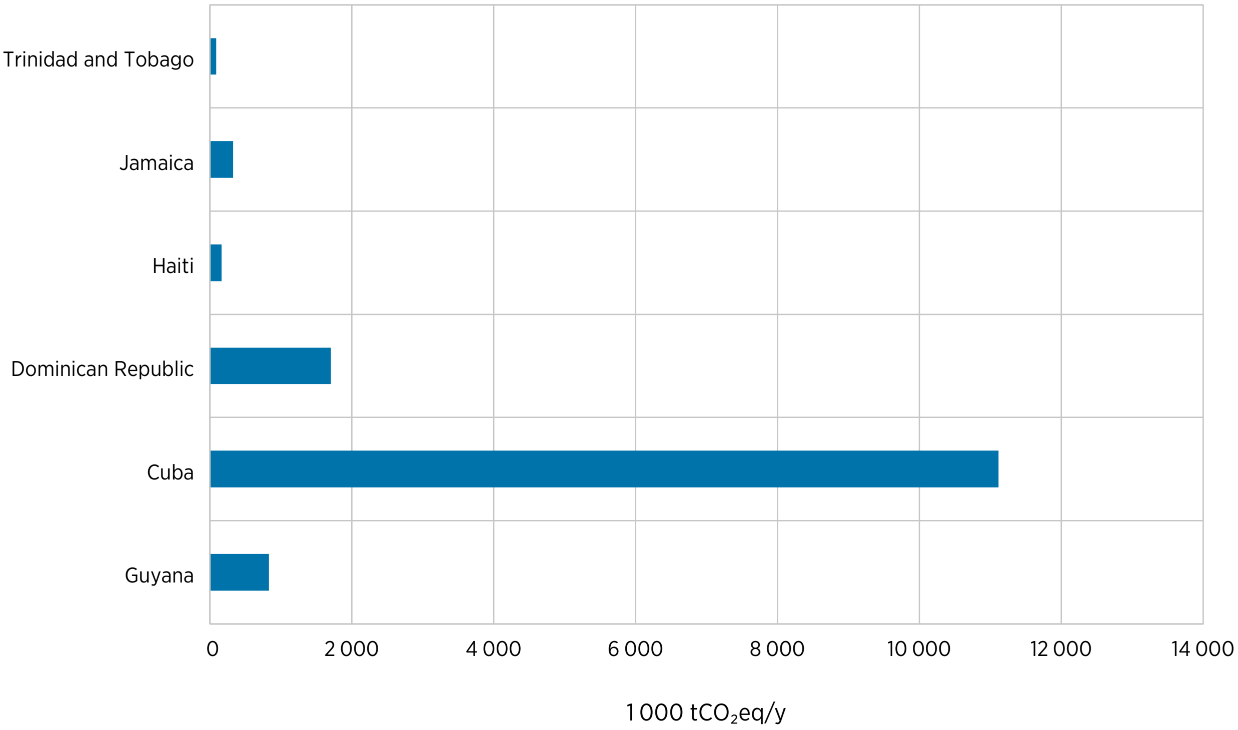
For the studied countries, the impact of sugarcane bagasse- and straw-based, oil-palm-solid-based and MSW-processing-based bioelectricity production on the mitigation of GHG emissions from conventional fossil-fuel-based thermal power plants was estimated for the highest production scenarios assessed in the previous section (Figures 33 and 34). The contribution of sugarcane biomass is the most relevant when compared with other biomasses.

Figure 32 CO_2 emissions avoided due to displacement of diesel by palm oil biodiesel for scenarios C2 and C3



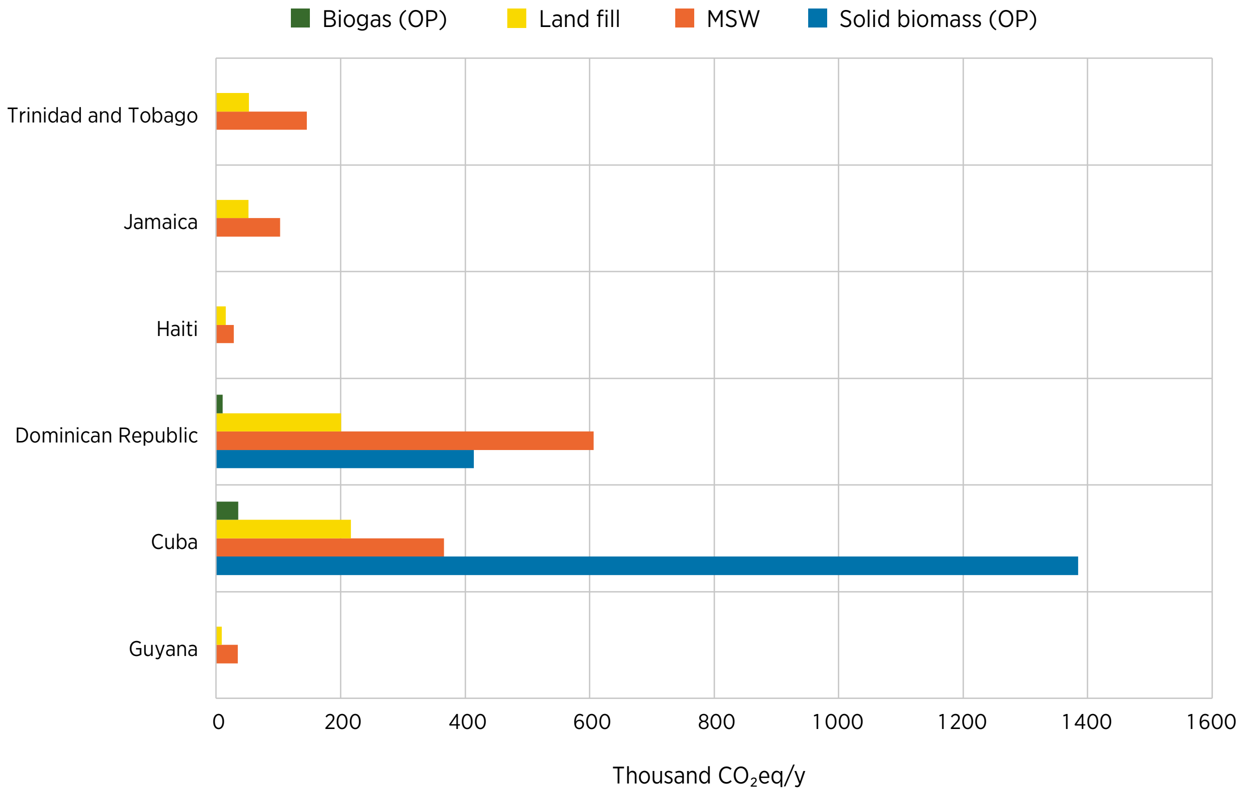
Note: tCO_2eq = tonnes of carbon dioxide equivalent.

Figure 33 CO_2 emissions avoided due to displacement of fossil fuels electricity by bioelectricity from sugarcane biomass (bagasse and straw), scenario C3



Note: tCO_2eq = tonnes of carbon dioxide equivalent per year.

Figure 34 CO_2 emissions avoided due to displacement of electricity by bioelectricity from oil palm biomass, biogas and MSW



Note: MSW = municipal solid waste; OP = oil palm; tCO_2eq = tonnes of carbon dioxide equivalent per year.

3.2. JOB OPPORTUNITIES

The literature on the social aspects of the bioenergy sector has produced estimates of job creation (direct, indirect and induced), which vary by region and other supply chain factors (Brinkman *et al.*, 2019). According to the latest edition of IRENA's Renewable Energy and Jobs annual review (IRENA and ILO, 2022), over 2 million people were employed globally in the liquid biofuel production chain; that is, for each gallon of biofuel produced in 2021, more than five jobs were generated worldwide. The South American and Caribbean region accounted for 44% of this employment generation. In the Caribbean countries, sugarcane ethanol production would potentially generate 179 jobs in Guyana in the C0 scenario, 3 030 jobs in Cuba, 873 jobs in the Dominican Republic, 281 jobs in Haiti and 133 jobs in Jamaica. Jobs would see a relevant increase in C3, of over 13 000 in Guyana, 136 000 in Cuba, 21 000 in the Dominican Republic, 34 000 in Haiti, 4 000 in Jamaica and 1 000 in Trinidad and Tobago. Therefore, considering all selected countries, job creation in the sugarcane industry can represent, depending on the scenario, 133 000 -137 000 employment opportunities. For biodiesel production, 6 000 to more than 37 000 jobs would be created in the palm agro-industry under the conditions established for Cuba and the Dominican Republic.

Projections in review (IRENA *et al.*, 2022) indicate that electricity production will create an average of 3.35 related jobs per GWh due to biogas, 0.44 jobs per GWh due to MSW incineration and 1.84 jobs per GWh due to the direct combustion of solid biomass, as observed in the palm and sugarcane industry. Under this vision, bioelectricity production in the Caribbean SIDS could promote more than 46 000 jobs, as can be seen in Figures 35 and 36, predominantly in the sugarcane sector.

Figure 35 Potential employment generated by bioelectricity production using sugarcane biomass

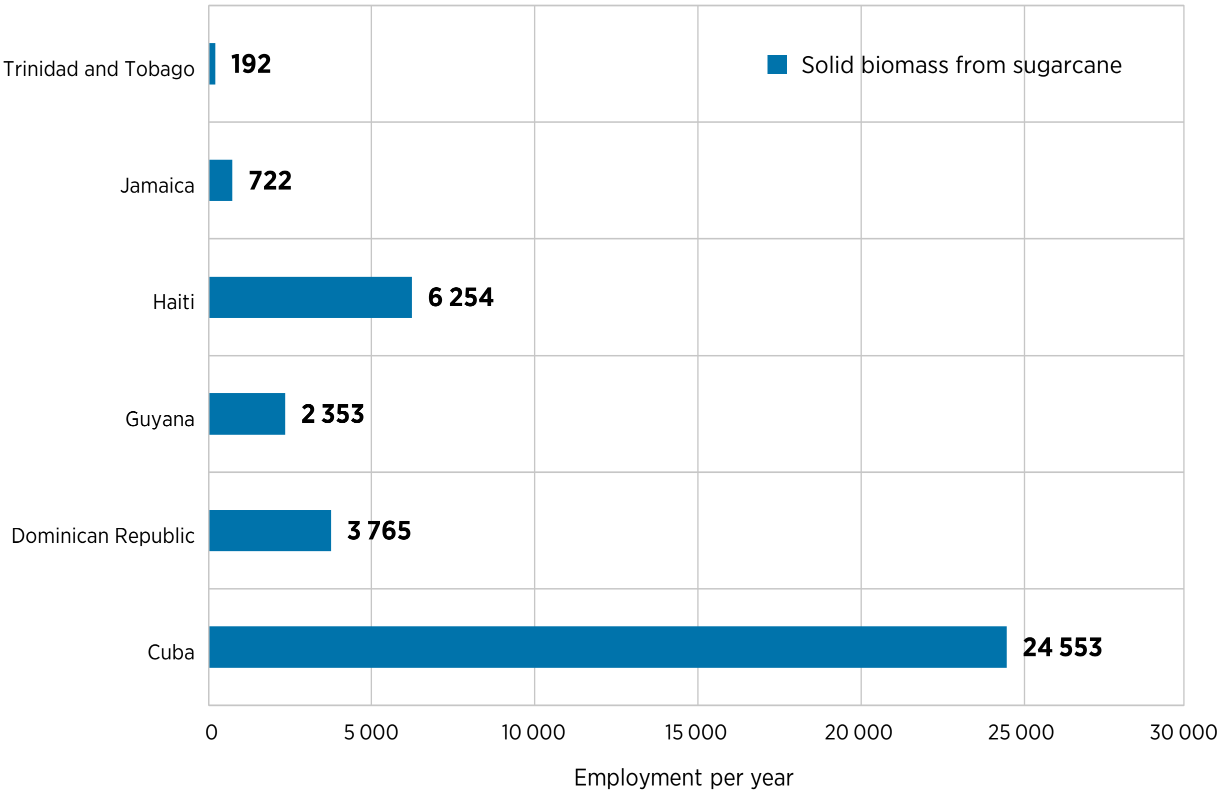
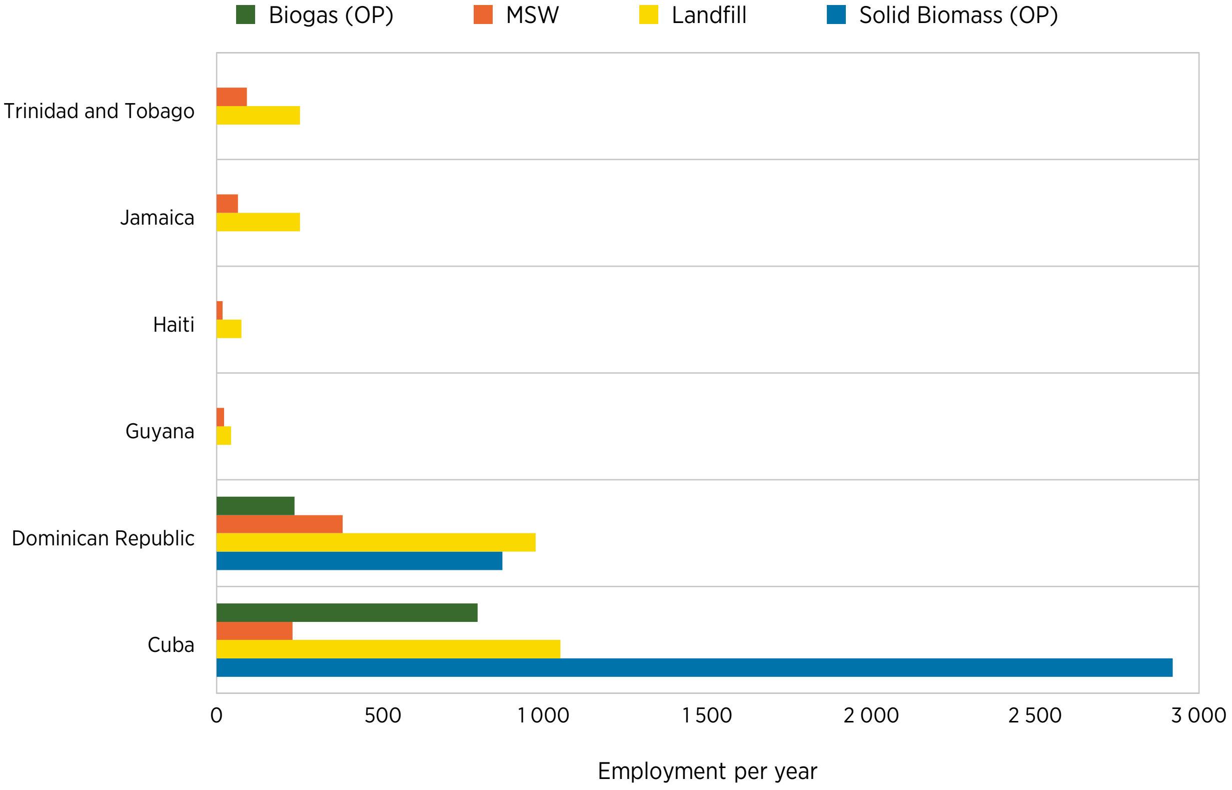


Figure 36 Potential employment generated by bioelectricity production using oil palm biomass, biogas and MSW



Notes: MSW = municipal solid waste; OP = oil palm.

3.3. ECONOMIC CONSIDERATIONS AND BENEFITS

The investment needed to expand sugarcane and oil palm production, and deploy modern sugar mills and biodiesel plants, was estimated considering the results for C3 scenario, which aimed at greater bioenergy production in the selected Caribbean SIDS, as evaluated in the bioenergy potential study. The following hypotheses were considered: (1) for sugarcane ethanol production, a representative mill with a capacity to crush 2 Mt of sugarcane per harvest season with 200 work days (able to crush approximately 400 t/h of sugarcane to produce 28 m^3 of ethanol); (2) for palm oil biodiesel production, a representative palm oil mill with the capacity to extract 1 Mt of FFBs per harvest season with 333 days (unitary capacity of oil extraction ~8 t/h and biodiesel production ~2 m^3/h); (3) a lifespan of 20 years for the processing plants and (4) in both cases, investment in the agricultural and industrial sectors corresponding, respectively, to 71% and 29% of the overall investment (MPOB, 2023; UDOP, 2023).

For estimating the investment in processing plants, the actual costs of existing plants with varied capacities were used as a reference, as shown in Table 26. The actual costs of existing plants were adjusted as shown in Eq. (4), with an inflation adjustment using the chemical engineering plant cost index (CEPCI) (Scott, 2020)and a scale factor of "α", which was adopted as 0.6 for biofuel processing plants (Julio *et al.*, 2021).

$$\text{Cost}_2 = \text{Cost}_1 \left(\frac{\text{Capacity}_2}{\text{Capacity}_1}\right)^{\alpha} \left(\frac{\text{CEPCI}_{\text{Dec 2019}}}{\text{CEPCI}_{\text{Ref. date}}}\right) \tag{4}$$

Table 27 presents a preliminary projection for the upper value of the total investment required for each country to implement the sugarcane and oil palm biofuel industry. Table 28 shows the annual investment required in the agricultural sector for the C3 scenario. The annual cost of investment considered two financing hypotheses, which entailed two distinct interest rates and payment periods: 8% interest rate and 15 years, and 12% interest rate and 10 years. Further, these values were related to the GDP, with data for 2019 (World Bank, 2022).

Table 26 Baseline cost data for investment forecasting

PLANT	COST (million USD)	CAPACITY (t/h)	REF. YEAR	$\text{CEPCI}_{\text{DEC 2019}}$	REFERENCES
Palm oil plant					
Palm oil mill	9.20	5.625	2006	499.6	(Vaskan, Pachón and Gnansounou, 2018)
Biodiesel plant	7.42	4.505	2008	575.4	(Gebremariam and Marchetti, 2018)
Sugarcane plant					
1G-Ethanol plant	43.27	500.0	2015	537.00	(Pereira *et al.*, 2018)

Note: CEPCI = chemical engineering plant cost index; $\text{CEPCI}_{\text{Dec 2019}}$: 607.5; t/h = tonnes/hour.

Table 27 Investment required for sugarcane and oil palm mills for C3 scenario

CARIBBEAN SIDS	NUMBER OF PLANTS		UNITARY INVESTMENT (THOUSAND USD)		TOTAL INVESTMENT REQUIRED (MILLION USD)	
	SC	OP	SC[a]	OP[b]	SC	OP
Cuba	54	10	34 252	101 702	1 858	1 008
Dominican Republic	8	3			285	301
Guyana	5	-			178	-
Haiti	14	-			473	-
Jamaica	2	-			55	-
Trinidad and Tobago	1	-			34	-

[a] Capacity to mill 2 Mt of sugarcane per harvest season with 200 days.

[b] Capacity to extract 1 Mt of FFBs per harvest season with 333 days.

Note: FFB = fresh fruit bunch; Mt = million tonnes; SC = sugarcane; SIDS = small island developing states; OP = oil palm.

Table 28 Annual investment required for C3 scenario (assuming an annual interest rate of 12%/8% and a 10-/15-year amortisation period) and ratio to GDP

CARIBBEAN SIDS	ANNUAL INVESTMENT REQUIRED (THOUSAND USD)[a]		ANNUAL INVESTMENT REQUIRED (THOUSAND USD)[b]		INVESTMENT RELATED TO GDP (%)			
	SC	OP	SC	OP	SC[A]	OP[A]	SC[B]	OP[B]
Cuba	217 112	117 812	329 376	178 472	0.21	0.11	0.32	0.17
Dominican Republic	33 292	17 387	50 506	26 339	0.04	0.02	0.06	0.03
Guyana	20 805	-	31 563	-	0.40	-	0.61	-
Haiti	55 299	-	83 892	-	0.37	-	0.56	-
Jamaica	6 385	-	9 686	-	0.04	-	0.06	-
Trinidad and Tobago	4 002	-	6 071	-	0.02	-	0.03	-

[a] 12% interest rate and 10-year term.

[b] 8% interest rate and 15-year term.

Note: GDP = gross domestic product; OP = oil palm; SC = sugarcane; SIDS = small island developing states.

The numbers in Tables 27 and 28 should be used cautiously since they represent a very preliminary assessment; however, they could give policy makers an initial idea, to be further detailed and better evaluated. In both financing hypotheses, the required annual investment is low compared with the GDP. The investment required in most of the assessed countries would thus account for less than 1% of the gross fixed capital formation over a period of 10 or 15 years. Assuming it will take 10 years to develop the biofuel production capacity estimated in the higher potential scenario, annual investment would be about 4% of the SIDS' gross capital formation.

Currently, only one of the Caribbean SIDS has a bioethanol or biodiesel blending mandate: Jamaica mandates 10% and 5% blending in ethanol and biodiesel, respectively. The other countries fulfil all of their gasoline and diesel consumption by import (EIA, 2022a). This confirms the feasibility of bioethanol and biodiesel as alternative fuels, which could be produced locally at competitive costs. Also, as a preliminary evaluation, taking into account the industry investment financed as outlined in the previous paragraph and the cost of processed feedstock, the cost of liquid biofuels produced in the Caribbean SIDS could range from USD 0.43-0.41/l of ethanol and USD 0.50-0.45/l of biodiesel. These costs are competitive with the current average international prices of gasoline and diesel.

4. CONCLUSIONS

This study confirms that bioenergy is a strategic asset for developing the Caribbean SIDS, besides supplying clean and affordable energy to the world. The initial question about the reasons to promote sugarcane-, oil-palm- and MSW-based bioenergy in these regions has many assertive answers, of which some are clearly indicated in this work: for instance, there exist resources, the required technology is known and available, there are domestic and global needs to meet and there are environmental benefits. These results are obtained using conventional bioethanol and biodiesel production techniques (*i.e.* first generation). Moreover, the use of such technologies to utilise energy from agro-industrial and municipal waste is technically efficient and economically viable.

Until a few years ago, biofuels were limited to a handful few countries. But growing environmental concerns, energy security and socio-economic development have led to their increased incorporation into the energy matrix of several nations.

The reasons to adopt fuels based on photosynthetic processes are many; one relevant reason is the decarbonisation expected from the substitution of fossil fuels, given that biofuels sequester carbon naturally (during their life cycle) and/or artificially through the implementation of carbon capture technologies, and are therefore considered low- or zero-emission energy sources (Nogueira *et al.*, 2020). Several industrialised nations (*e.g.* the United States, the European Union countries, Australia and Canada) and a growing number of emerging economies, led by Brazil, have hence adopted biofuels for use in transportation and electricity production, with an aim to reach their decarbonisation goals and the Sustainable Development Goals (SDGs) (mainly SDG 7, 8, 9 and 13).

In line with this, the latent potential for the development of liquid biofuels in the Caribbean SIDS is extremely relevant. The objective of this development is to diversify liquid biofuel production, considering predictability; environmental, economic and social sustainability; and compatibility with market growth. There are several proposals, each with its own frame of reference, to formulate principles, criteria and indicators to quantify and evaluate liquid biofuel chains' environmental performance.

Sustainable bioenergy development in the Caribbean SIDS will depend essentially on stable policies, with support from long-term prospects, for example, international agreements on carbon emission mitigation and global biofuel trade. These policies should integrate economic, social and environmental considerations, and propose land use and rural development plans; this is consistent with measures to minimise biofuels' potential adverse impacts through the application of sustainability guidelines focused on topics such as biodiversity, GHG emissions, and land and water utilisation.

Specifically regarding the sustainability of sugarcane- and oil-palm-based bioenergy production – the crops selected in this study – it is worth mentioning that there are concerns about, for example, their impacts on food production and prices, the effects of monoculture, labour conditions and deforestation. These issues have been studied extensively and, in many cases, they are real and must be considered. Nevertheless, on many other occasions, bioenergy is a key alternative, which can be promoted under sustainable environmental, social and economic conditions, with important and positive impacts, as indicated by several studies abroad (Souza *et al.*, 2015). Both contexts have been found in developing countries and should be known as examples to avoid or follow. Bioenergy systems are not always good, but in many cases, they can be very important, sustainable and desirable.

It is thus essential to acknowledge that instances of 'problematic projects' predominantly stem from inadequate governance and poor land management rather than the biophysical characteristics of specific crops. This nuanced perspective is of paramount importance, especially in a global quest for every conceivable sustainable solution toward decarbonisation. In essence, countries should explore all potential options, contextualising them within local settings and relying on factual data. A carefully crafted combination of strategies that involve activating and regenerating degraded land, valorising waste streams, and creating incentives from nature-based solutions such as carbon credits, can effectively finance both bioenergy and conservation, thus reinforcing local food, fibre, and energy security, especially for developing countries.

Finally, Table 29 presents a synthesis of the opportunities for and barriers to modern bioenergy deployment in the studied Caribbean SIDS.

Table 29 Opportunities for, and barriers to, modern bioenergy in the selected Caribbean SIDS

OPPORTUNITIES	DEPLOYMENT BARRIERS
• The countries included in the study have attractive and significant technical potential to deploy modern, competitive and reliable bioenergy systems that can produce liquid biofuels for transport and generate electricity to be sold to the grid, and are implemented with efficient and well-known technologies. • Liquid biofuels (ethanol and biodiesel) can be easily introduced in the existing vehicular fleet equipped with internal combustion engines. • Promoting modern bioenergy requires implementing modern and sustainable agricultural practices and appropriately managing organic municipal and agro-industrial waste and co-products, generating social and environment benefits. • Modern bioenergy has an important role in energy sector decarbonisation, and in achieving and fulfilling national greenhouse gas mitigation targets and pledges. • Biomass-based electricity is dispatchable and can back up the increasing generation capacity based on intermittent renewable energy. • Bioenergy projects can attract foreign and domestic direct investments and foster development in related areas. • Modern bioenergy can stimulate new alliances between engineering companies and academic institutions, inducing mutual improvement in energy technologies and management. • Besides increasing the environmental sustainability of Caribbean countries, bioenergy generation will also help increase energy security, diversify the national energy mix, reduce fuel imports, and simultaneously tackle waste management issues in SIDS where population growth is contributing to increasing MSW. • In the medium term, liquid biofuels produced from waste and residues can be additional sources of biofuels. • The development of well-designed and balanced feed-in-tariffs can encourage private sector participation in power generation, as has been proven in Brazil and elsewhere.	• In many countries, the higher cost of biofuels compared with fossil fuel alternatives (*e.g.* gasoline or diesel) is the principal barrier limiting biofuels' application, besides current fossil fuel subsidies. • Modern bioenergy requires programs to encourage green energy investments; for example, bioenergy provisions for senior credit, corporate tax relief, land rent abatement and power purchase agreements. • Political insecurity is a cross-cutting impediment to promoting biofuels for transportation, and it hinders investment in advanced biofuels, given the long lead times associated with projects. In this regard, stability of the legal framework and institutional foreseeability are essential to support the necessary development of technical standards and other specific regulations. • For the indicated bioenergy pathway, to address sustainability concerns as production scales up, support must be provided to constantly train bioenergy stakeholders in agricultural crop yield and, subsequently, agricultural residue production. These activities are site specific, and local governments should promote investment in research and development to develop, improve and diffuse techniques and processes in biomass production. • Although bioenergy technologies are generally open, they can be difficult to access and finance, due to their potential risks and associated market uncertainties. It can be beneficial to recognise these hurdles and establish co-operation programmes. • The absence of appropriate infrastructure is also a crucial obstacle. Biofuels' expansion for transport requires complementary investments in storage, transport and distribution infrastructures. • Besides inadequate landfills, many small island developing states also have inadequate landfill layouts, which do not include leachate and gas collection systems, and are also poorly managed without proper separation or sorting facilities.

Note: SIDS = small island developing states.

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