BARBADOS

BIOMASS in the ZERO-ENERGY TRANSITION

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1. DEVELOPMENT CHALLENGE

1.1 Context and global significance

Country context

Barbados has a population of about 287,708 people in 2021[1] on a land area of 430 km^2. The country had a gross domestic product (GDP) of USD 4.90 billion in 2021[2] (USD 3.9 billion in power purchase parity in 2020). The country also scores high on the Human Development Index[3] and the gender development index[4] but the last poverty survey still showed almost 20% of persons living in poverty. With a GDP per capita of USD 15,163 in 2020, it is ranked as a high-income country. On the other hand, many products and items need to be imported leading to a high import bill and a high cost of living[5]. Given its small economy and dependency on imports (including most of its fuel needs), the country is highly susceptible to global economic shocks.

Energy and electricity

Energy policy and planning are under the responsibility of the Ministry of Energy and Business (MEB)[6]. Until 2013, the state-owned Barbados Light and Power Company Limited (BLPC) had the exclusive right to supply energy for all public and private purposes. BLPC was privatised with the Canadian-based Emera Inc. requiring a total of 79.9% of shares during 2010-11. Tariffs, quality standards and other matters concerning the relationship between BLPC and its customers, are regulated by the Fair Trading Commission (FTC) under the Utilities Regulation Act (2002; amended 2020). Barbados' oil and gas sector is concentrated around a few key players, the state-owned National Petroleum Company (NPC) and its daughter company Barbados National Oil Company Limited (BNOC) together with the private fuel distributors Sol and Rubis. In principle, market pricing is adopted, the main exception being natural gas (which is imported/produced along with crude by BNOC and has traditionally been sold at sub-market prices, i.e., prices below competing fuels).

Barbados' total primary energy consumption hovers around 15-17 exajoules (EJ) and this level of consumption is about the same level as in the early 1990s. Most of Barbados' energy is imported, although the country does produce crude oil, natural gas, and biomass. The share of energy produced indigenously as a proportion of the total energy supply has fallen since 1990, from 34% to 15-17% in recent years. Over the period 1990 to 2019, oil products have been the dominant energy type in Barbados. The reduction in bio-energy use reflects the decline in the sugar industry and the use of its residues for (on-site) power and heat generation. Electricity generation accounts for almost 40% of total fossil fuel imports (diesel and heavy fuel oil), while 40% is consumed by the transport sector. Fuel imports amounted to about USD 250 million, equivalent to about 11% of GDP, in 2018. As a result, energy costs are relatively high in Barbados, as is the case

1 Barbados is densely populated with 668 people per m^2 (source: knoema.com). Population growth is small, 0.13% in 2019 and 0.12% in 2020

2 The economy increased from USD 3.1 billion in 2002 to USD 4.9 billion in 2021. Per capita GDP increased from USD 11,284 in 2001 to USD 15,163 in 2020. Barbados position on the Gender Development Index (GDI) was 1.034 (on a scale 0.45-1.1) in 2020

3 Scoring 0.788 in 2020. For comparison, Norway scored highest in 2021 at 0.957 and Niger lowest, 0.394. The country's Gross National Income (GNI) was USD 12,167 (in constant 2017 PPP USD). Source: hdr.undp.org

4 Gender Development Index of 1.034 (UNDP, 2021, available at https://hdr.undp.org/gender-development-index#/indicies/GDI

5 For example, in worddata.info's cost-of-living index Barbados is placed 121 (USA=100). However, the purchasing power index is 19.5 (again, USA=100), implying that in relation to the monthly income (USD 1392 in Barbados vs USD 5869) people can buy less goods.

6 In 1978, an 'Energy Division' was created under the Ministry of Commerce. Over time, 'energy' has been under the purview of various government entities. Over time, 'energy' has been under the purview of various government entities. For example, in 2010, the Division of Energy and Telecommunications (DOET) was set up within the Prime Minister's Office in 2020 'energy' came under the purview of Ministry of Energy, Small Business and Entrepreneurship (MESBE) which was rebranded Ministry of Energy and Business (MEB) in 2022.

Box 1 Energy balance, Barbados (2020) and annual electricity generation

(in terajoules, TJ)	Oil	Oil derivatives	Natural gas	Sugarcane and products	Renewable energy	Electricity	Total
Production	1,012		386	391	293		2,082
Import		15,761	223				15,984
Export	2,010						2,010
Stock	998	-301	-16				681
Supply	0	15,460	593	391	293	0	16,737
Transformation		-6,133	-207	-35	-247	3,534	-3,088
Own use and distr. losses		0	19	0	0	316	335
Final use		9,327	367	356	46	3,218	13,314
- Transport		4,686				6	4,692
- Residential		349	96		30	1,036	1,511
- Industry and agriculture		3,859	23	356		772	5,010
- Commerc., instit., other		433	248		16	1,404	2,101

Source: compiled from UN, OLADE, BLPC and MEB Statistics

(in GWh)	2020	2021
Electricity generation	983.17	985
- by renewable energy	68.7	84.6
- losses	60.4	57.2
Net generation	922.8	927.8
- parasitic load	28.9	22.8
Electricity sold	893.9	905.0
Average tariff (BBDc/kWh)	43	50

(in MW)	2021
Total capacity	356.2
- fossil fuel	286.4
- renewable energy (RE)	69.8
-- utility-scale (solar)	10.0
-- distributed RE (solar)	59.8
Peak load demand	140.6
Baseload demand	106.0

Source: Data compiled from MEB's Energy Bulletins 2020 and 2021, BLPC website, and the IRRP (MottMcDonald, 2021)
Distributed solar power had increased to 55 kW in 2021 (provided by 2503 connections) and currently (Oct 2022) stands at 60 kW (provided by 2639 connections) and expected to increase to 100 kW by 2030. See: https://energy.gov.bb/dashboard/.
Exchange rate has been stable at USD 1 = two Barbadian dollar (BBD) during 2020-2022 (www.exchangerates.co.uk)

in many Small Island Developing States (SIDS). The fuel bill for electricity generation alone was USD 176 million in 2017 (3.8% of GDP)[7].

Electricity in Barbados is produced by thermal power plants, 252 megawatts (MW) in total owned by the now privatized utility Barbados Power & Light Company (BPLC) and by about 51.8 MW of solar capacity (10 MW in plants and 41.8 MW distributed[8]). Energy production was about 983 GWh in 2020 and 985 GWh in 2021, of which 68.7 GWh was renewable energy in 2020 and 84.6 GWh in 2021[9].

Greenhouse gas emissions

According to the Second National Communication (2018), Barbados' net greenhouse gas emissions amounted to 1,930 kilotons of CO_2 equivalent (CO_2e) in 2010, which represents less than 0.01% of the global total in that year. Total emissions were 1,984.5 ktCO_2e, of which the energy sector was responsible for 74% of the emissions (1457 ktCO_2e) and the waste

7 Based on statistics at OLADE website and the from Energy Bulletins 2020 and 2021

8 In 2017, BLPC commissioned a 10 MW solar farm, while over 1,900 rooftop systems are installed by households, private business and public sector. Data: BLPC website

9 Source: Energy Bulletins 2020 and 2021

sector 15% (295 ktCO_2e). Total removals were 54.5 tCO_2e[10]. Of the total emissions, 1,490 kilotons were CO_2 (and 325 ktCO_2e) of methane emissions. OLADE gives an estimate of energy-related emissions of 1737 ktCO_2e in 2010, 1575 ktCO_2 in 2015 and 1161 kilotons of CO_2e in 2020[11]; indicating that emissions are declining over time indicating lower energy intensity of the economy and a beginning penetration of renewables (solar) in the energy supply.

The country is also vulnerable to the effects of climate change, in particular, flooding and wind damage (although less so than other Eastern Caribbean nations[12]). Barbados ranks among the countries with the lowest available freshwater resources per capita in the world.

1.2 Baseline situation

1.2.1 Energy and electricity

Barbados' energy mix is dominated by fossil fuels which are subject to the volatility of the global market price. The Government of Barbados (GoB) is well aware of the unsustainability of the country's energy sector both from the economic viewpoint of expensive fossil fuel imports as well as the global environmental perspective. Also, MEB has taken steps to put the sector, including BLPC, on a pathway towards a more competitive, low-carbon electricity generation market.

Box 2 Feed-in tariffs, Barbados

Technology, Size Category	FIT BDS cents/kWh	Allocation MW
Customers below 1 MW		
Solar, up to 10 KW	42.75	5
Solar, above 10 KW to 100 KW	44.75	
Solar, above 100 KW to 250 KW	41.75	8
Solar, above 250 KW to 500 KW	38.25	
Solar, above 500 KW to 1 MW	36.25	12.7
Land-Based Wind up to 10 KW	39.75	3
Land-Based Wind up Above 10 KW up to 1 MW	38.25	
Anaerobic Digestion, up to 1 MW	44.25	2
Solid Biomass, up to 1 MW	52.25	2
Total Allocation		32.7
Customers between 1 and 10 MW		
Solar PV, above 1 MW and up to 5 MW	23.25	30
Land-Based Wind 1 MW and up to 50MW	22.25	10
Total Allocation		*40*
Solar PV Above 5 MW and up to 10 MW	21.75	25
Land-Based Wind Above 5 MW and up to 10 MW	20.25	10
Total Allocation		*35*

<u>Independent power production</u>

In recent years there has been a growing interest in decentralised electricity generation, both at the household level (based on increasingly affordable roof-top PV) and also for MW scale distribution or transmission-connected PV generation. This has been encouraged under the Feed in Tariff (FiT) arrangement. In 2010, a FiT pilot was started, known as the Renewable Energy Rider (RER) program. With the new Electric Light and Power Act (ELPA) of 2013, the market opened to independent power producers (IPPs) while respecting the rights granted under BLPC's licence until 2028[13]. In September 2019, the FTC approved a feed-in tariff (FIT) framework for RE technologies for

[10] Due to abandonment of managed lands (plantations), forest and grassland conversion and removals from soils

[11] Source: sielac.olade.org

[12] Despite the fact that Barbados has not suffered a catastrophic hurricane impact in the last 50 years, it has suffered loss and damage from 13 rainfall events between 1998 and 2017 and 10 tropical cyclone events between 1990 and 2017. Source: CCRIF Excess Rainfall and Tropical Cyclone models.

Retrieved from https://www.ccrif.org/sites/default/files/riskprofiles/XSR2.5_Annex2_r1.pdf and https://www.ccrif.org/sites/default/files/riskprofiles/TC_Annex2_r2.pdf

[13] The current license will expire in 2028. The Government has progressively sold its shares in the company until BLPC became 100%-owned by Emera Caribbean Inc in 2015. https://www.emera.com/companies/regulated-electric/emera-caribbean

installations up to 1 MW. FIT tariffs are differentiated by technology and project size, based on their levelized cost of energy (LCOE) and a multiple criteria analysis (MCA) of costs and benefits[14].

Customers must obtain BLPC's approval before interconnection to the grid. Any power generator above 5 kW domestic or 25 kW non-domestic that is connected to the utility grid must apply for a licence, to be reviewed and granted by MEB. A connection impact assessment, conducted by BL&P, is required for RE systems sized 150 kW and above. The (generation) licensing process verifies that a project complies with all relevant regulations including the existence of a Grid Connection Agreement, Power Purchase Agreement, and General Liability Insurance.

As of 2021, the licensing process for RE project developers is partly integrated with a web-based software application[15]. The FiT targets power plants below 10 MW, while larger power plants will be developed as IPPs under tenders led by MEB. The renewable energy industry is supported through a series of tax incentives introduced by the GoB. Some of these incentives are a zero value-added tax rate on all renewable energy and energy-efficient systems and products produced in Barbados; an income tax holiday of 10 years for developers, manufacturers, and installers of renewable energy products; and a 150 % deductible on expenditures for staff training, marketing of products for the sale of electricity, and product development or research that is related directly to the generation and sale of electricity[16]. Accelerated depreciation or "frontloading" of FiT tariffs to improve the cash flow during early project years is not foreseen in order to oblige RE operators to maximise energy production over the full 20-year period.

Energy policy

Barbados is ahead of other Caribbean island nations in its energy transition progress, leading the pack in the implementation of renewable energy feed-in tariffs, public renewable energy demonstrations (solar PV and solar thermal), and energy efficiency appliance labelling standards[17]. As an expression of the need to continue transitioning the country's energy sector, the Barbados National Energy Policy (BNEP 2019-2030) sets the goal of 100% renewable energy by 2030[18]. Barbados has embarked on an ambitious plan to introduce renewable energy (RE) generation, energy storage systems and electric mobility to replace fossil-based technologies. Reaching the 100% RE goal will require the installation of 635 MW of renewable energy of which solar energy (205 MW solar plants and 105 MW distributed) and on- and off-shore wind (300 MW). To be able to absorb the variable solar and wind supply, the grid would need battery storage of about 200 MW (68 MW decentralised and 132 MW centralised). About 15 MW is to be provided by biomass and waste-to-energy facilities. The Integrated Resource and Resilience Plan (IRRP, 2021) has slightly different figures with about 860 MW of installed renewable energy capacity by 2030 (of which about 23 MW installed bioenergy capacity). Bioenergy plays an important role in supplementing BESS (battery energy storage systems) to stabilise the energy supplied by the variable solar and wind energy. he Energy Policy and other related frameworks are neither gender sensitive nor gender responsive and are still somewhat limited in their approach to stakeholder engagement beyond the energy sector itself.

The National Petroleum Corporation (NPC) currently has approximately 21,200 customers of which approximately 1,000 are commercial entities[19]. There is continued demand for piped natural gas for cooking as an alternative to liquified

14 Customers are billed under one of the two arrangements: A) *All/Sell All Arrangement* (customers are billed under their regular electricity rate (inclusive of VAT) for all the energy consumed, regardless of the source. They then receive a credit on the bill for all the electricity generated from the RE system at the FIT or RER credit rate. Presently, customers with systems larger than 3 kW must be billed under this arrangement). B) *Sale-of-Excess* (customers with renewable energy systems 3kW or smaller are permitted be under this arrangement, in which customers are billed under their regular electricity rate (inclusive of VAT) for what they use from the grid and will receive a credit for the excess electricity sold to the grid. Customers under the pre-existing RER programme maintain their arrangement (BBS 0.416/kWh for solar PV)

15 Since February 2022 the new online system is the only method to apply for an ELPA licence. Applicants must complete the ELPA application on the system and submit all requisite documents related to the project, such as analyses, regulatory certificates, correspondences from financial institutes and other related documents

16 More details on incentives can be found in the *Renewable Energy and Energy Efficiency Fiscal Incentives Booklet for Individuals and Companies* (Energy Division, MESBE)

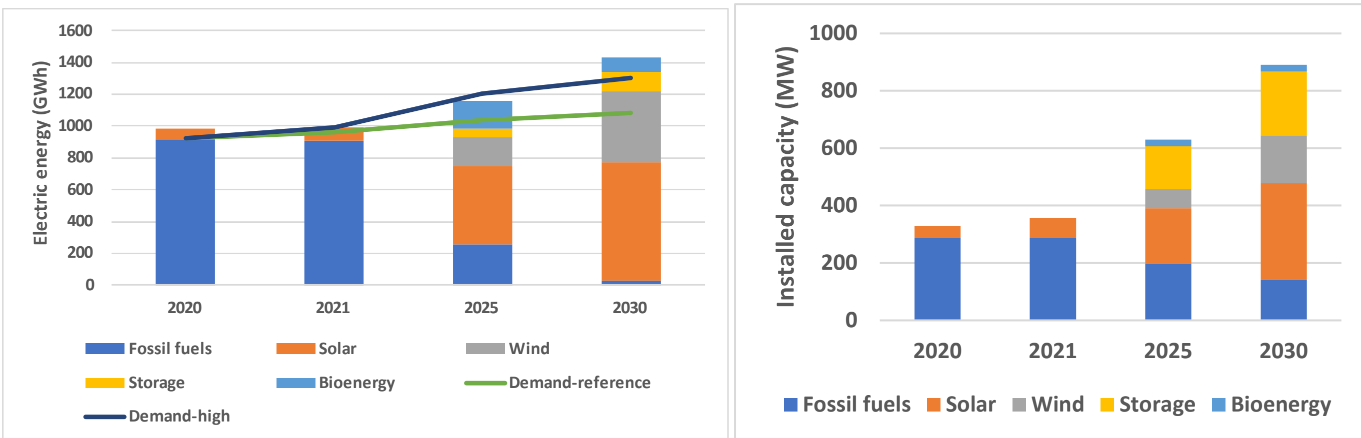
17 US Department of Energy, Energy Transitions Initiative, Barbados Energy Snapshot, https://www.nrel.gov/docs/fy20osti/76636.pdf

18 The milestones and specific targets are as follows: fossil fuel reduction: 49% (2023) and 100% (2030). Increase in renewable energy: 52% (2023) and 100% (2030)

19 Based on *The Future Role of Biomethane,* NPC position paper

petroleum gas (LPG) influenced by the current pricing mechanism for natural gas and convenience. Similarly, industries

Box 3 Energy pathway towards the 100% renewable energy target, Barbados



Left: electric energy generated (column), following IRRP scenario 3 and projected electricity demand (lines)
Right: installed capacity (in MW) in IRRP scenario 3.

Source: Data compiled from Draft Integrated Resource and Resilience Plan (IRRP), MottMcDonald (2021). Of the three scenarios developed in the IRRP, scenario 3 (with about 98-99% renewable power generation by 2030) was taken as a basis for the Barbados IRRP Action Plan (Acelerex, 2022)

use natural gas as the fuel source for their boilers. with a significant amount of distributed rooftop solar PV and battery storage, widespread use of electric vehicles and the discontinuation of the use of natural gas, it is anticipated that consumers (households currently using natural gas or LPG) may switch to energy-efficient, modern electric stoves.

Utility-scale and distributed renewable energy

Starting in 1974, amid an international oil crisis, Barbados invested in the area of solar water heating (SWH). Currently, there are approximately 50,000 solar water heaters in Barbados, with more than 35,000 domestic installations. With about 100,000 dwelling units in Barbados, this shows a significant penetration by the industry into the domestic market[20]. On the other hand, penetration seems to have reached its peak for some time and penetration has been slowing down in recent years as tax incentives have been removed. The government has the target to raise the number of domestic SWHs by 50% before 2025.

In the 'RE 100%' goal scenarios, about 750MW of installed RE-based power capacity would be needed by 2030[21]. To be able to accommodate such a large amount of variable RE, storage capacity needs to be built, in conjunction with smart grid technology. Lithium-ion (Li) batteries are a technically and commercially proven technology with widespread adoption, in particular in applications that support the adoption of variable renewable energy. A project is being developed by Hidrogène de France (HDF) Energy and Rubis with a capacity for 128 MWh of green hydrogen storage that will be coupled with 50 MW of solar power[22].

[20] Source: https://www.ctc-n.org/resources/seizing-sunshine-barbados-thriving-solar-water-heater-industry
Barbados Sustainable Energy Industry Market Assessment Report (CCREEE, UNIDO; 2019)

[21] The IRRP scenario 3 mentions 141 MW of fossil fuel based capacity, 223 MW of storage and 750 MW of non-fossil energy (337 MW solar, 166 MW wind, 23 MW biomass/waste/landfill) available installed capacity by 2030 (IRRP, MottMcDonald, 2021). About 390 MW to be installed in the period 2020-2025, in addition to the available capacity of 42 MW renewable energy (basically distributed solar PV) in 2020. Of which in 2025: 151 MW solar, 66 MW wind and 23 MW of biomass/waste/landfill, backed up by 250 MW of storage capacity.

[22] Supported by IFC and IDB financing. Source: https://h2eg.com/h2-view-news-ifc-and-idb-invest-support-plans-for-green-hydrogen-plant-in-barbados/. Hydrogen storage uses surplus electrical energy to generate hydrogen that acts as the energy carrier. The operation consists of an electrolyser and a storage medium, typically a high-pressure vessel. During the charge cycle the electrolyser splits water molecules into oxygen and hydrogen. The hydrogen is then stored or can be injected into the gas network. During discharge, the

PV is seen as having a strong potential for development in the Barbados market due to the ease with which it can be integrated into areas such as electric vehicles, construction in sustainable and hurricane-resilient roofs, and battery storage systems being developed by BLPC. It is modular nature and the ease with which it can be expanded in installed systems makes it an attractive choice. It is also a well-understood and accepted technology by both people within the industry and general consumers. In the IRRP scenario (100% RE), about half of the renewable power would be generated by solar (496 MW generating 750 GWh annually in 2030). The first utility-scale solar PV farm was commissioned in 2018, the 10 MW ground-mounted facility in Lambert's, St. Lucy (owned by BLPC), is generating an estimated 20.2 GWh annually.

While wind energy has not taken off significantly, there are plans to develop this technology to complement existing solar installations, including off-shore wind, of about 180 MW in total (generating 442 GWh annually in 2030). Apart from Pavana Energy Ltd.'s 1 MW onshore wind installation in the southwest parish of St. John (consisting of four 2.5 kW turbines), BLPC is investigating the possibility of establishing a wind farm in Lambert's, St. Lucy alongside the existing PV farm there (10 MW, consisting of five 2.3 MW turbines).

Net metering has been allowed in Barbados since 2010, and consumers with wind and/or solar self-generation facilities have been able to supply energy to the national grid until recently, via the Renewable Energy Rider and Feed-in Tariff programmes. Until the large utility-scale RE facilities are set up, decentralized PV is likely to become the most significant contributor to the renewable energy mix in the short run. The government has set a distributed generation target of having at least 35,000 buildings with rooftop or ground-mounted solar PV systems that are resilient to extreme wind events (e.g., Category 4 Hurricanes)[23]. In the IRRP (2021), the generation by distributed renewables (rooftop PV) is expected to increase to about 100 MW by 2030 (generating 150 GWh annually. Total installed capacity stood at about 41.8 MW in 2021 (see Box 1). The development of distributed RE has been facilitated by the Feed-in Tariff policy and projects supported by development partners[24]. However, some barriers and gaps remain to achieve a doubling of the distributed RE capacity as envisaged in the IRRP (2021) and are targeted to be addressed in the SMARTER project (discussed in Section 2).

1.2.2 Bioenergy resources and potential

<u>Bioenergy potential and resources</u>

There is significant potential to scale up biomass production at a national level during the transition to a 100% renewable energy matrix. Biomass resources can be converted following various pathways to provide fuel for thermal application or electricity generation or as biofuel for transportation, and other uses (see Box 4 for an overview).

Biomass resources: bagasse, vinasse and energy crops

Historically the vast majority of the Caribbean islands were highly dependent on sugar cane cultivation before tourism became predominant. Sugar was introduced to Barbados by the colonizers in the 15th century and provided Britain with sugar and rum. In this period, the arable land crop rotation was one-third sugar cane, one-third food crops of yam, sweet potatoes, guinea corn or maize, and one-third pasture for the plantation animals. There were 500 plantations on the

hydrogen can be combusted in boilers, turbines, or reciprocating engines to produce electricity in conventional power plants along with natural gas or in a fuel cell can be used to directly convert the hydrogen into electricity and water. In general, there are concerns about water for hydrogen, stating that obtaining water for the economy will be too expensive or demanding on the water and energy requirements. Barbados is the most water-scarce western hemisphere nation. The production of 128 MWh requires 1 ton of H_2, for which 9 ton of water is needed. to avoid creating any additional burden on freshwater usage, seawater can be used can be purified through desalination processes before being used as an electrolysis feedstock. adding a desalination process increases the energy requirement of the life cycle of electrolytic hydrogen production, but this too is negligible in comparison to powering the electrolyzer itself

[23] BNEP 2019-2030

[24] Including the UNDP/GEF Disaster Risk & Energy Access Management (DREAM) project, 2015-2019 and the IDB/EU projects Public Sector Smart Energy Programme (PSSEP), since 2013m, and Smart Fund II (since 2019). See Box 12 for more details

island. However, over the past decades, sugarcane production has declined from 1.23 million tonnes in 1971 to 146,831 in 2018[25] and 81,064 tonnes in 2020[26] .

Barbados classifies about 16,000 ha of its surface area as arable land. Farming still represents an important land use (about 10,000 hectares). Apart from sugarcane, other crops are yams, sweet potatoes, corn, eddoes, cassava, and several varieties of beans and vegetables. The sugarcane area harvested fell gradually from 19,000 ha in 1971 to 2,160 ha in 2020. With the decline, the number of factories was shrunk, from about ten to the two that are still operational today, Andrews Sugar Plantation and Factory in St. Joseph and Portvale in St. James. The public holding company Barbados Agricultural Management Corporation (BAMC) owns the Portvale sugar mill. Private farmers and producers are organised in the Barbados Sugar Industry Limited (BSIL).

With sugar exports dropping farmers have looked for other opportunities. New speciality products have begun appearing in the retail market, carrying the Barbadian sugar trademark. Also, producing feedstock (molasses) for the growing rum distilleries is an assured market[27]. Plans have been put forward for a large-scale switch to high-fibre canes for energy purposes (in particular, elephant grass, and king grass[28]) that are currently grown as fodder by farmers, for energy purposes. King grass has also been proposed for dedicated energy crop production. Apart from the king grass, other plants, such as Leucaena (river tamarind), are being explored. Energy crops may be grown as dedicated annual crops (harvested once a year on the same land), part of double cropping (harvesting twice in a year), part of rotational cropping (different crops grown on the same piece of land in rotation) or as cover crops (crops grown when land would normally be left fallow between 2 harvests). Cover crops or double crops, on the other hand, help in avoiding the food-and-fuel conflict and prevent land use change and soil erosion. Digesting the crops in bio-methanation and applying the left-over digestate contributes towards maintaining the soil carbon content and overall fertility.

During the sugar and ethanol processes, waste products are produced that can be used to generate biogas. These are the straw, bagasse, vinasse and filter cake, that is, 1000 kg of sugarcane stalks generate as waste 140 kg of straw (dry basis), 280 kg of bagasse (wet basis) and 40 kg of filter cake[29] (wet basis). In Barbados, straw is left on the field as mulch to provide nutrients to the land after a harvest. Bagasse is the dry, pulpy, fibrous material that remains after the sugarcane stalk has been crushed to extract its juice and is used as a fuel within the sugar industry. Following the production of sugarcane juice by milling the cane stalks, the juice is clarified, concentrated, and centrifuged to produce sugar and a syrup called molasses. Molasses is sent to be fermented in tanks where a liquid known as wine or fermentation wine is retrieved. This wine is centrifuged to recover the fermentation yeast which will be reused, and the liquid portion is sent to be distilled. In rum production, the distillation of wine separates the ethanol from the waste product also known as vinasse, which has a high organic content. The vinasse is either treated onsite and used to fertilize fields in irrigation systems or pumped through a pipeline and dumped into the sea.

The increased and sustainable domestic food production has, on the other hand, also received attention (in view of Barbados' expenditures worth over USD 300 million on food imports) affecting its commercial balance and food security. With the larger share of inputs for the tourism sector being imported, domestic supplies would provide an opportunity to add value and retain a larger part of earnings in the country. Therefore, the Ministry of Agriculture prioritizes using land for food production rather than other uses, and due to the limited land space in Barbados, the growth of plants in monoi-cropping for energy purposes is disfavoured. Local cultivation of king grass in rotation with sugar cane (or other

[25] Of the 140,830 tonnes, about 100,985 was produced on plantation area, 45,208 by BAMC and 638 by small farmers. Source: Barbados Economic and Social Report 2018

[26] knoema.org. The decline was influenced by the end of the preferential treatment of Caribbean nations by Europe. Agricultural land area fell from 19,700 hectares to 10,000 in the same period. Correspondingly, Barbados produced more than 159 000 tonnes of sugar in 1968, in 2018 sugar production was just about 11,700 tonnes. https://basonevoice.org/wp-content/uploads/2018/01/AgroFestMag-17.pdf

[27] Foursquare, Mount Gay, WIRD (West Indies Rum Distillery) and St Nicholas Abbey. Barbados exports some USD 80 million worth of rum annually. https://barbadostoday.bb/2020/01/17/rum-makers-report-rising-sales/

[28] Four species are referred to as 'elephant grass', including the African *Cenchrus purpureus*, also known as Napier grass, Uganda grass or king grass

[29] During the purification process, sugarcane juice is separated from solids that collect to the bottom of the storage material. This fibrous solid component is known as filter cake. Filter cake is used to fertilize soils and replenish nutrients.

crops) offers a possibility of feedstock supply whilst ensuring that supporting industries are not affected. This may offer opportunities for the financial viability of sugar farmers with additional revenue yearly outside of the sugar industry.

Another option considered, given local constraints, is the exploration of cultivating and harvesting king grass, wild cane or other dedicated energy crops in regional countries such as Guyana[30] and Suriname. Such crops may offer even higher yields than traditional sugar cane, but it has not been demonstrated yet that new crops (dedicated, inter-cropped or as imported feedstock) are agronomically, environmentally and economically appropriate.

Moreover, a reconversion to other commodity crops is unlikely to happen as long as a broader orientation on future agricultural land use in Barbados has not taken place. This orientation will take place in the framework of population growth and structural changes in the economy, with a view to (i) land conservation, (ii) local food production, (iii) reduced labour availability for the agricultural sector; (iv) land use conversion (from sugar production into non-agricultural uses including construction and tourism); (v) search for economic diversification and job opportunities, and, (vi) analysis of this potential and or ways identified to ensure that women farmers and other actors can benefit from such opportunities.

Biomass resources: crop and animal residues

The collection and valorisation of organic waste streams fit into a circular economy approach. Besides sugar cane trash and stalks, significant biomass waste flows are available in the form of bagasse (from sugar processing), vinasse (from rum production), food and waste oil residues, animal waste (manure), as well as the organic content in municipal solid waste (MSW) and wastewater.

The Ministry of Agriculture does not support the use of arable lands to grow crops for the specific means of biomass (as mentioned, it is considered detrimental to the food supply). However, the Ministry is supportive of waste-to-energy. Crop residues are materials such as leaves, stems and roots that are left unused after a harvest and lower quality crops not fit for consumption. These have the potential to be used as bioenergy in thermochemical conversion or biochemical. However, crop residues are a great source of organic matter that can be highly advantageous in maintaining or improving soil quality or, used as animal fodder. Additionally, crop residue can be used to make compost which can be tilled into the soil to provide nutrients and residues. In Barbados, the largest amount of crop residue comes from the sugar cane plant. Other sources of crop residues include cotton stalks and root crop residues.

Livestock is part of the local agriculture industry providing food such as dairy, meat, and eggs for local consumption. Manure can be obtained from dairy farms, beef lots, poultry and pig farms. The manure of farm animals found locally (cattle, pigs, sheep and chicken) may be treated via anaerobic digestion. The digestion of cattle/pig manure is an established technology and has been implemented widely all around the globe on varied scales. Digestion of poultry manure is trickier and often mixed with other manure. Pigs are often contained in sties or pens resulting in easier management of their manure. Cows and sheep are often left on pastures to graze (making it difficult to collect their manure), although both sheep and cow manure are commercially available and used by crop farmers in Barbados).

Biomass resources: municipal solid waste and wastewater

The Barbados Waste Characterization Study 2015 estimates the amount of municipal solid waste as about 26,036 tons a month in 2015 with an organic content of 15,667 tons a month, implying a total of 4.07 kg of waste per person per day. Of this amount, 24,921 tonnes a month passed through the Sustainable Barbados Recycling Centre (SBRC) facility at Vaucluse, St. Thomas (a public-private partnership) and 1,115 tonnes by the different recycling entities. After recovering materials for recycling, the waste ends up in the Mangrove landfill next to SBRC. The Sanitation Service Authority (SSA) is responsible for the collection and delivery of waste to the Mangrove Landfill. The commercial and industrial sectors utilize private waste haulers for the collection and delivery of waste to the Mangrove Landfill.

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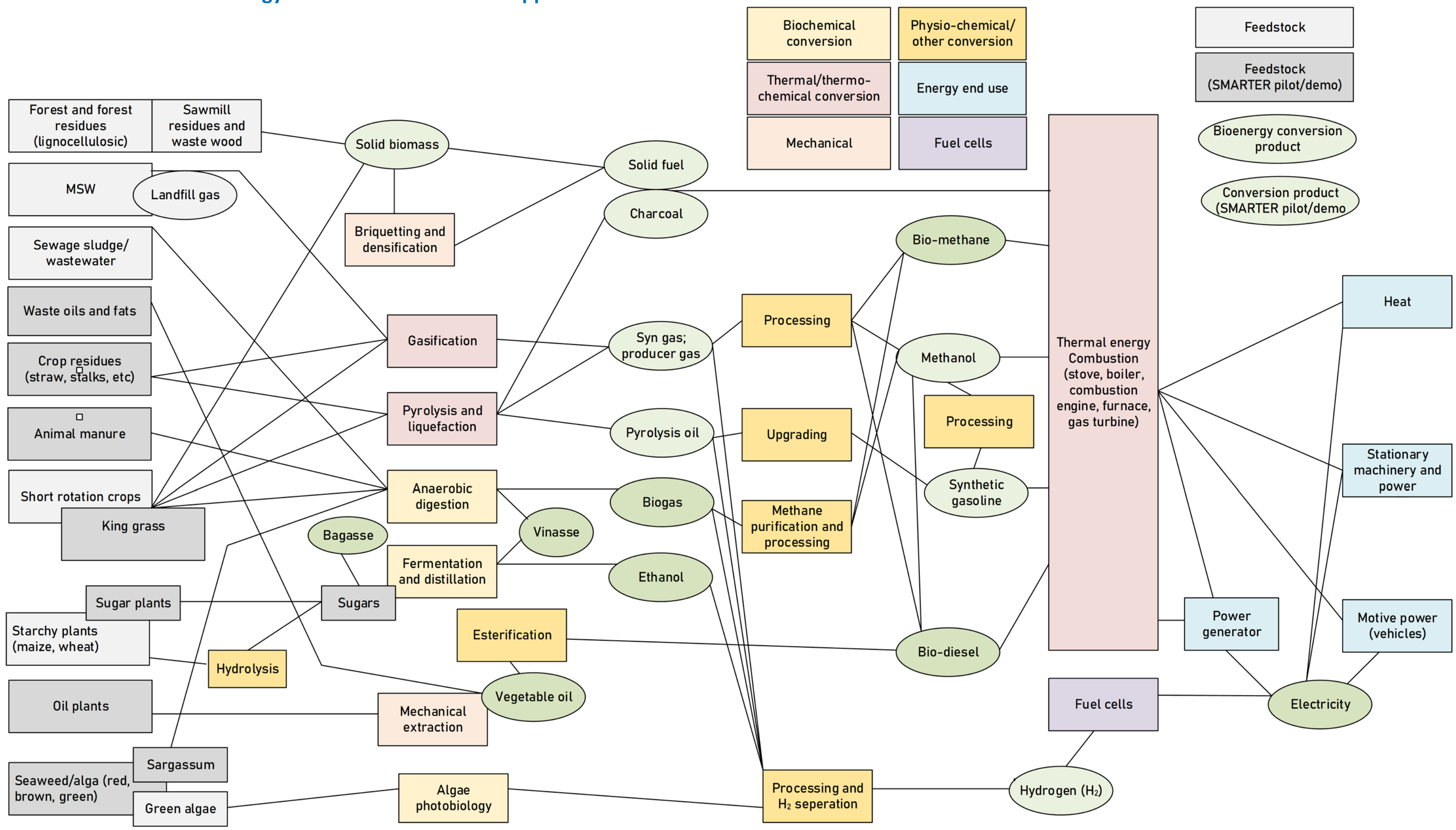
[30] Apparently, land could be leased for about USD 5 per acre in Guyana. Source: p.c. stakeholder meetings

Box 4 Overview of bioenergy resources – conversion -applications



At SRBC some separation of organic waste occurs. This happens at their facility before landfilling occurs, however, the only organic materials utilized as compost are clean organics (grass cuttings, coconut husks etc.). The bulk of food waste (from the residential, business and tourism sectors) is likely to be mixed with residual waste ending up in the landfill. An estimated 44% of the waste going to the landfill is food waste . This organic content will decompose over time but the resulting landfill gas (a mixture of methane and carbon dioxide) is vented and not used.

The Barbados Water Authority (BWA) is the entity in Barbados charged with supplying the island with potable water as well as the provision of wastewater treatment and disposal services. Wastewater management happens in two sewage treatment plants on the island – Bridgetown & South Coast. Both treatment plants discharge the effluent water out to sea but the sludge generated from the Bridgetown Plant is disposed of on land. The waste from the South Coast is collected in a 'skip' and disposed of in the island's landfill. There have been some problems recently with the South Coast Sewerage system. There is no gas usage from the waste treatment system.

Biomass resources: sargassum

Caribbean countries, including Barbados, have battled abnormally large influxes of sargassum[31] seaweed since 2011 due to a combined oceanic-atmospheric event in 2011 concurrent with increased eutrophication of the ocean in estuaries of the Amazon and Orinoco River deltas[32]. The species has become a plague in coastal seas around Barbados and on other Caribbean coasts affecting the ecosystem The phenomenon has been affecting tourism and fisheries[33] negatively, resulting in economic losses. Rotting Sargassum seaweed on coastlines cost USD 120 million in beach restoration costs throughout the Caribbean in 2018; this number does not include the economic effect of hotel closures and occupancy drops because of sargassum which also has regional economic implications[34]. Sargassum should be removed promptly from the shoreline to avoid vast accumulations of unsightly decomposing seaweed which makes its collection more difficult. Besides producing public health risks[35], it has an unpleasant smell. Manual collection of shored Sargassum with rakes or by hand is simple but tedious incurring costs proportional to the size of the workforce employed. More efficient is using a combination of beach grooming and self-propelled collection vehicles such as mechanized surf rakes (which can go together with beach cleaning in tourist areas)[36]. An even better solution to collect Sargassum seaweed in terms of its environmental impact is near-shore collection, by seaweed harvesters and shallow water vessels.

Anaerobic digestion has been proven successful at converting a wide array of brown algal species into bio-methane[37] [38]. Sargassum seaweed is now arguably the region's largest single biomass resource, for example, delivering 24 million tonnes of biomass influx into the Caribbean Sea in June 2022[39] and showing a cyclic but reliable year-long presence in floating

31 Sargassum, named after the Sargasso Sea in the North Atlantic Ocean, is a genus of brown macro-algae

32 Johns, Elizabeth M., Rick Lumpkin, Nathan F. Putman, Ryan H. Smith, Frank E. Muller-Karger, Digna T. Rueda-Roa, Chuanmin Hu et al. "The establishment of a pelagic Sargassum population in the tropical Atlantic: biological consequences of a basin-scale long distance dispersal event." Progress in Oceanography 182 (2020): 102269.

33 Decaying sargassum releases hydrogen sulphide that can kill marine life while sea turtles may become entangled in sargassum rafts or impede access to beach nesting sites blocked by sargassum.

34 https://www.nationnews.com/2019/07/30/us120m-for-seaweed-clean-up/

35 Resiere, Dabor, Hossein Mehdaoui, Jonathan Florentin, Papa Gueye, Thierry Lebrun, Alain Blateau, Jerome Viguier et al. "Sargassum seaweed health menace in the Caribbean: Clinical characteristics of a population exposed to hydrogen sulfide during the 2018 massive stranding." Clinical Toxicology 59, no. 3 (2021): 215-223.

36 One reported issue is these mechanical collection vehicles may disrupt turtle nests and kill baby turtles who might be asleep just under the surface of the sand

37 Henry, Legena, Brittney McKenzie, Aria Goodridge, Karyl Pivott, Joshua Austin, Kristen Lynch, Shamika Spencer et al. "Experimental evidence on the use of biomethane from rum distillery waste and Sargassum seaweed as an alternative fuel for transportation in Barbados." Energy Division/Infrastructure and Energy Department: Washington, DC, USA (2021).

38 Thompson, Terrell M., Pedram Ramin, Isuru Udugama, Brent R. Young, Krist V. Gernaey, and Saeid Baroutian. "Techno-economic and environmental impact assessment of biogas production and fertiliser recovery from pelagic Sargassum: A biorefinery concept for Barbados." Energy Conversion and Management 245 (2021): 114605.

39 https://www.abc.net.au/news/2022-08-04/caribbean-sargassum-seaweed-endangers-animals-industry/101298784

rafts visible by satellite [40]. In Barbados, the University of West Indies (UWI) is exploring the co-digestion of *Sargassum* with other forms of organic waste (such as manure from sheep farms and vinasse from rum distilleries)[41] to produce bio-CNG to fuel cars.

Conversion routes: thermochemical

Biomass cogeneration[42] has been used by the sugar cane industry in Barbados for years by combustion of the bagasse. With the decline of the sugarcane industry, also the use of its residues in the energy supply went down from an average 1,820 TJ in 1970-1979 to 391 TJ in 2020[43]. The Portvale sugar mill, the only one remaining in operation, produces electricity from co-generation but is not connected to the main grid (about 10 GWh generated in 2020 by about 1.5 MW during crop season). The potential to generate power from bagasse is larger, about 5-6 MW, which could generate about 40 GWh of power per year. The bagasse production was 60,000-70,000 tonnes around 2014[44] but down to about 25,000 tons by 2020.

For environmental and other reasons, the public has not been receptive of incineration. The Vaucluse Biogas Power Plant is a 20-25 MW biopower project[45]. It is planned in Saint Thomas, Barbados, which uses municipal solid waste[46] as feedstock with gasification as the conversion process to release the energy value of the feedstock. The project (with an estimated USD 320 million cost) is currently in permitting stage, and if approved, could start construction in 2023 or thereafter.

Conversion routes: biochemical

Anaerobic digestion involves a series of biological processes in which microorganisms break down biodegradable material in the absence of oxygen. The process initially produces biogas (composed primarily of methane, 50–70% and carbon dioxide, 30–50%), leaving digestate, a nutrient-rich solid fraction that can be used as an organic fertiliser. A wide range of biomass feedstocks are indigenous to the Barbadian environment and can be processed by anaerobic digestion, such as manure, crops and crop residues, wastewater, beverage waste, and the organic portion of municipal solid waste (e.g., food waste). Beyond these industries, the recent introduction of invasive species such as river Tamarind and Sargassum seaweed are also viable sources of freely available and can be processed by anaerobic digestion.

A separate collection of food waste is necessary for the recovery of energy and nutrients via anaerobic digestion. Separate food waste collection from households and businesses is not yet a local practice but is expected for local inclusion as the country transitions to sustainable energy practices. It is envisioned that organic waste normally delivered to the landfill is diverted to a biogas plant. Also, the commercial and industrial sectors can be encouraged to separate organic waste with the provision of waste bins to collect materials including food waste and delivered them to the plant using the same private waste haulers currently utilized. The digestion of the collected food waste will result in reduced GHG emissions from landfills (less methane) and extend the operation years of local landfill cell sites. In order to capture all available food waste for anaerobic digestion by 2030, associated policy and legislation must be implemented to ensure the separation of organic waste from other municipal solid waste.

Several stakeholders, Barbados Agricultural Management Company (BAMC), Barbados Sugar Industry Limited (BSIL) and private farmers, have been in discussion to establish Grow Energy, a company aimed at producing sugar cane by-products and biomass energy. Other initiatives have also looked at using biomass feedstock for biomethane generation. A

[40] https://optics.marine.usf.edu/projects/SaWS/pdf// See Sargassum outlook_2022, Bulletins 01, 04, 07 and 10

[41] See the website www.rumandsargassum.com

[42] Combined production of heat (used on-site) and electricity (used on-side or delivered to power grid)

[43] https://sielac.olade.org

[44] 2014 respectively, https://www.tilasto.com/en/topic/energy-and-environment/bagasse/production/bagasse-production/barbados. 2020: own estimate

[45] The total Barbadian MSW would be sufficient to/ generate only about 20%, so 3-5 MW, thus implying that other feedstock is used, such as agricultural or imported food waste from Caribbean neighbours.

[46] https://www.nationnews.com/2020/07/09/waste-to-energy-plant-on-the-way/

collaboration between Circular Fuels LLC and West Indies Rum Distillery (WIRD) has been proposed to utilize sugar cane residues and other feedstocks like sargassum to generate biogas.

The Barbados Investment and Development Corporation (BIDC) recently issued a Terms of Reference (ToR) for the design and installation of a 250 kWh anaerobic digestion plant, estimated to require 6000-12,000 tons of biomass input annually to generate 2 GWh of electricity annually. Feedstock proposed includes food waste, roadside grasses, and industrial wastewater from BIDC's industrial estates, the biogas generates is then to be injected into the national energy grid.

End-use: electricity or direct use of biomethane

The above-mentioned project concepts prioritize using waste to generate electrical energy. Another option is to use upgraded biogas as a natural gas substitute (to be injected into the natural gas grid) or as an LPG alternative. In the BNEP 2019-2030, the demand for natural gas and other fossil fuels would need to be replaced by electricity (e.g., electric cooking or electric vehicles) or gradually substituted by biomass-derived fuels. Currently, BNOC provides about 1.6 million ft^3 of natural gas to its approximately 21,000 customers and produces about 1 million ft^3 of natural gas a day[47]. The demand for natural gas is likely to grow (due to demand growth in sectors such as tourism and due to replacing of oil products to achieve fossil fuel-free status by 2030).

To ensure economies of scale and cost efficiencies concerning the size of anaerobic digestion plants and biomethane upgrading facilities, NPC-BPOC envisages a central bio-methanation facility at the BNOC natural gas plant at Woodbourne, St. Philip that should be able to produce 700 million ft^3 of gas to feed into NPC's pipeline system. The biogas would be procured from a range of feedstock, including vinasse, food waste, and pig slurry year-round, while Sargassum could be used when blooms arise, and king grass will be cultivated for use alongside Sargassum seaweed. With IDB support, a feasibility study will be carried out on the potential of the above-mentioned feedstock, while a 'request for proposals' for such a facility is under preparation.

Biofuels for transportation

There were 135,742 vehicles on the island in 2020 of which 19,214 ran on diesel, 116,182 on gasoline and 346 electric vehicles[48]. The transport sector was responsible for 33% of the energy consumed in the country (see Box 1). The 2030 "100% RE" vision calls for the elimination of the use of diesel and gasoline for local transport over the next decade. This will require either retrofitting the existing fleet and/or restricting the importation of conventional vehicles and incentivising the importation of electric and alternative renewable fuel vehicles. Incentives have been introduced for electric vehicles[49]. The 'high demand' scenario in the IRRP (2021) assumes a penetration of electric mobility approaching 100%, while a base (reference) scenario assumes 60% (and a low demand scenario a more modest 30%). These strategies currently do not include significant considerations of gender and women's empowerment.

Apart from the increasing electrification of the vehicle fleet[50], the other sustainable option is replacing fossil fuels (gasoline and diesel) through the increased use of ethanol and biodiesel as transport fuels. Biodiesel can be produced from waste vegetable oil and certain crops, such as rapeseed, soybean, coconut, sunflower and other oily crops.

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47 In 2021, natural gas production was 372.9 billion ft^3, imports were 301.2 billion ft^3 and sales 576.2 ft^3 (the difference is formed by stock). Sources: a) Energy Bulletin 2021; b) BNOC Request for Proposal Services for the designing, building and commissioning of a Biomethane Facility (2018);c) The Future of Biomethane, NPC Position Paper

48 See NPC *Feasibility Assessment of Including Liquid Biofuels in the Transport Sector* (2020) based on data provided by Ministry of Transport, Works and Maintenance (2020). This includes 35 electric buses, of which some were provided by IDB projects (see Box 12)

49 A two-year tax holiday on electric vehicles was introduced in April 2022, while discussion is ongoing whether to extend to hybrid vehicles as well. Hybrid electric vehicles (HEV) are powered by an internal combustion engine and an electric motor, which uses energy stored in batteries and cannot be plugged in to charge the battery. Plug-in hybrid (PHEV) can be plugged in, while still having an internal combustion engine. Government workers (who had been allowed to borrow up to BDS 50,000 interest-free for vehicle purchase) will now have that increased to BDS 100,000 if they purchase an electric or hybrid vehicle. https://barbadostoday.bb/2022/03/15/electric-cars-tax-breaks-but-new-alternate-levy/

50 The IRRP 2021 sees electricity demand in transport increase from the current 2 GWh to between 273 and 455 GWh (of a total electric energy demand of 1,424 GWh) in 2030, depending on the electric vehicle penetration

Regarding the replacement of gasoline, a low-hanging hanging fruit is the installation of CNG kits into gasoline cars, which can then be driven on biomethane from upgraded biogas derived from anaerobic digesters[51]. This transition activity could gradually transition the whole gasoline fleet. Any gasoline car, via a 4-hour CNG kit installation, can drive on either its original liquid fuel or the gaseous renewable fuel. This would coincide with the sale of CNG cars currently on sale in neighbouring Trinidad and Tobago[52]. A disadvantage for many car owners will be the CNG tank occupying most of the boot space, especially in smaller vehicles[53]. A second option, which would be comparable in cost but slower in implementation, is mixing ethanol at 10% (E10) for the whole gasoline fleet, followed by a gradual insertion of hydrous ethanol usage (E100) driven by the replacement of the gasoline vehicle fleet for imported flex-fuel vehicles. This may be time to implement as it would require switching to E10 nationwide at the fuelling stations (see Annex G.6 for more details)

Similar to gasoline, biodiesel would be mixed with mineral diesel at 20% (B20) for the whole diesel fleet, followed by the gradual inclusion of B100 usage driven by the diesel vehicle fleet renewal through the import of vehicles approved for the use of B100. Currently, a biodiesel pilot is implemented by Barbados National Terminal Company Limited (BNTC) on the mixing of bio-diesel (produced locally from cooking oil waste). To be able to produce B10 in sufficient quantities to transform the diesel market (currently, demand is about 6.40 million litres a month) would require 0.64 litres of bio-diesel, which cannot be produced from the country's cooking oil waste alone. Land use as well as biofuel production and cost will pose limitations on local production of crops, thus requiring the (expensive) import of bio-diesel, or import of feedstock (e.g., soybean oils) or the cultivation of crops of leased land abroad.

1.3 Relevance to national priorities

This Project is aligned with Barbados' priorities and reports under the UNFCCC including its Second National Communication (SNC, 2018) and the Nationally Determined Contribution (NDC, 2015; update 2021). The SNC explicitly mentions that "Barbados is dedicated to the implementation of sustainable energy technologies, including wind, solar, cogeneration and waste-to-energy strategies". Barbados has not submitted a Biennial Update Report (BUR). The SMARTER initiative is closely aligned with Barbados National Energy Policy (BNEP 2019-2030) and its Implementation Plan (2018). It is also supportive of the Barbados Physical Development Plan (PDP, amended 2016), specifically Chapter 3 – Land Use and Built form Policies; the National Agricultural Policy (NAP, 2013) and the 2020 Water Protection and Land Use Zoning Policy. The Project is also aligned with the National Climate Change Policy Framework which is monitored by the National Climate Change Committee of the Ministry of Environment and National Beautification (MENB).

At a regional level, as a CARICOM member, Barbados has been actively involved in the formulation and implementation of the CARICOM Energy Policy and the underlying Caribbean Sustainable Energy Roadmap and Strategy (C-SERMS) that were approved in 2013). CARICOM's Caribbean Centre for Renewable Energy and Energy Efficiency is hosted by Barbados.

Box 5 Policy and plans related to energy and electricity

Policy / planning document	Relevance
Barbados Sustainable Development Policy (2004)	The over-arching goal of this policy is to ensure the optimisation of the quality of life for every person by ensuring that economic growth and development do not occur to the detriment of our ecological capital. Although formulated well before, the Policy links with actions plans for 24 sectors with the UN Sustainable Development Goals adopted in 2050

51 Henry, Legena, Brittney McKenzie, Aria Goodridge, Karyl Pivott, Joshua Austin, Kristen Lynch, Shamika Spencer et al. "Experimental evidence on the use of biomethane from rum distillery waste and Sargassum seaweed as an alternative fuel for transportation in Barbados." Energy Division/Infrastructure and Energy Department: Washington, DC, USA (2021).

52 http://www.ngvjournal.com/noticias/trinidad-and-tobago-to-install-five-cng-stations-2/?lang=es

53 Another smaller disadvantage is a power drop experienced depending on the driving. Sufficient CNG filling stations and service and maintenance facilities need to be available

Policy / planning document	Relevance
Barbados National Energy Policy (and Implementation Plan), 2019	The BNEP aims to achieve a 49% fossil fuel reduction by 2023 and a 100% fossil fuel reduction by 2030. The above fossil fuel reduction targets can be stated as increased production of energy from renewable energy targets for electricity generation of 52% in 2023 and 100% by 2030. It is the Government's policy to phase out local consumption of natural gas by 2030, replacing natural gas with an appropriate renewable fuel(s). Significant additional investments are now needed for the BNEP goal of 100% renewable energy to be attained by 2030. To this end, a draft Integrated Resource and Resilience Plan (IRRP) has been formulated that will guide the implementation of the BNEP
Electric Light and Power Act (ELPA), 2013 and subsequent Amendment Bills (2015, 2019)	The Electric Light and Power Act, 2013 (ELPA) sets the government's priorities in the electricity sector which are to reduce electricity prices, increase energy security, promote the use of cleaner fuels, and reduce negative environmental impacts. The Electric Light and Power Act 2013 (ELPA) is "an Act to revise the law relating to the supply and use of electricity, to promote the generation of electricity from sources of renewable energy, to enhance the security and reliability of the supply of electricity and to provide for related matters". It replaced the original 116-year-old Electric Light and Power Act which was passed in 1899 and was further amended in 2015.
Fair Trading Commission Act, 2002 and subsequent Amendment Bill (2020)	The Fair Trading Commission assumed regulatory responsibilities on January 2, 2001, under the Fair Trading Commission Act, CAP. 326B. The Commission is responsible for the enforcement of the provisions of the Utilities Regulation Act, CAP. 282, the Telecommunications Act, CAP. 282B, the Fair Competition Act CAP. 326C and the Consumer Protection Act
National Climate Change Policy (2012) Second National Communication (SNC; 2018) Barbados Nationally Determined Contribution (2016; update 2021)	The SNC explicitly mentions that "Barbados is dedicated to the implementation of sustainable energy technologies, including wind, solar, cogeneration and waste-to-energy strategies". Barbados has not submitted a Biennial Update Report (BUR) as yet. The Barbados Nationally Determined Contribution (NDC) of 2015 mentions that Barbados intends to achieve an economy-wide reduction in GHG emissions of 44% compared to its business-as-usual (BAU) scenario by 2030; i.e. in absolute terms, translating to a reduction of 23% compared with the baseline year, 2008. A fossil fuel-free electricity sector represents a significant enhancement of the 2015 NDC target of 65% renewable energy, alongside a 22% improvement in energy efficiency in the electricity sector. In the 2021 NDC Update, Barbados' conditional mitigation contribution for 2030 consists of: 1. a 95% share of renewable energy in the electricity mix, 2. 100% electric or alternatively-fueled vehicles in the passenger fleet; 3. a 20% increase in energy efficiency across all sectors as compared to BAU; 4. a 29% decrease in industrial, commercial and residential fuel consumption as compared to BAU; and 5. a 20% decrease in waste emissions. Barbados adopts the following ambitious contributions for 2030: • 35% reduction relative to business-as-usual emissions in 2030 without international support (unconditional). • 70% reduction relative to business-as-usual emissions in 2030 conditional upon international support.
Barbados Sargassum Adaptive Management Strategy (SAMS)	After the Prime Minister declared Sargassum to be a national emergency, the country is postured via the SAMS to find uses of Sargassum that meet the crisis at its current scale. The question of bioenergy for Barbados is the only at-scale question when it comes to Sargassum management[54] [55].
Barbados Physical Development Plan (PDP) (Draft) Amendment, 2017[56]	Requirements for the Environmental and Social Impact Assessments (ESIA) vary and have been identified in relevant sections of the PDP policies but may also be subject to the discretion of the Environmental Impact Assessment Committee. However generally the several types of industrial plants require an ESIA, a) chemical or petroleum manufacturing, c) desalination plant; d) power

54 Henry, Legena, Brittney McKenzie, Aria Goodridge, Karyl Pivott, Joshua Austin, Kristen Lynch, Shamika Spencer et al. "Experimental evidence on the use of biomethane from rum distillery waste and Sargassum seaweed as an alternative fuel for transportation in Barbados." Energy Division/Infrastructure and Energy Department: Washington, DC, USA (2021). Thompson, T. M., B. R. Young, and S. Baroutian. "Pelagic Sargassum for energy and fertiliser production in the Caribbean: A case study on Barbados." Renewable and Sustainable Energy Reviews 118 (2020): 109564.

55 See https://www.cavehill.uwi.edu/cermes/projects/sargassum/docs/sams/draft_vol_02_barbados_sams_appendices_12feb21.aspx

56 Planning and Development Department. (2017). PDP Resources. Retrieved from http://townplanning.gov.bb/physical-development-plan/pdp-resources/

Policy / planning document	Relevance
	generation plant; e) cement plant (or other plants for the burning of lime or bricks). This also applies to any other industry where the process is potentially obnoxious or dangerous to health and amenity because of excessive smell, fumes, smoke, dust, grit, ash, noise or vibration.
Planning and Development (Environmental Impact Assessment) Regulations, 2021[57]	According to these regulations, an Environmental Impact Assessment Committee, appointed by the Board, functions to screen applications for planning permission to determine whether an environmental impact assessment is required in any case.
Institutional frameworks and conventions, signed by Barbados	*Biodiversity and sustainable resource management* • Convention on wetlands of international importance, especially as waterfowl habitat (1971) • Convention on international trade in endangered species of wild fauna and flora, with appendices (1973) • Convention on Biological Diversity (1992) *Climate change and natural disasters* • Vienna Convention for the Protection of the Ozone Layer (1985) • United Nations framework convention on climate change, with annexes (1992) • Kyoto Protocol (1997) • Agreement Establishing the Caribbean Community Climate Change Centre (CCCCC) (2002) • Agreement Establishing the Caribbean Disaster Emergency Management Agency (CDEMA) (2008) • Paris Agreement on the United Nations Framework Convention on Climate Change (2015) *Community health, safety and security* • Universal Declaration on Human Rights (1948) • Inter-American convention on the granting of political rights to women (1948) • Convention on the Political Rights of Women (1953) • International convention on the elimination of all forms of racial discrimination (1965) • International Covenant on Civil and Political Rights (ICCPR) (1966) • Convention on the Elimination of all Forms of Discrimination Against Women (CEDAW) (1979) • Convention on the Rights of the Child (CRC) (1989) • UN Declaration on the Elimination of Violence Against Women (1993) • Inter American Convention on the Prevention, Punishment and Eradication of Violence (1994) • Beijing Declaration on and Platform for Actions (1995) • CARICOM Charter of Civil Society (1997) • Convention on the Rights of Persons with Disabilities (2007) *Cultural heritage, labour and working conditions* • International Covenant on Economic, Cultural and Social Rights (ICECSR) (1966) • Labour and Working Condtions • Equal Remuneration Convention (1951) (No.100) • Discrimination (Employment and Occupation) Convention (1958) (No. 111) *Pollution prevention and resource efficiency* • Montreal protocol on substances that deplete the ozone layer, with annexes (1987) • Basel Convention on hazardous wastes (1989) • Rotterdam Convention on the Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade (1998) • Stockholm Convention on Persistent Organic Pollutants (2001) • Agreement establishing the Caribbean Centre for Renewable Energy and Energy Efficiency (CCREEE) (2017)

57 The Government of Barbados. (2021). Planning Development (Environmental Impact Assessment) Regulations, 2021. Retrieved from https://www.barbadosparliament.com/uploads/bill_resolution/0179f618229127d8d28f9ee3dd239511.pdf

2. BIOENERGY POTENTIAL IN BARBADOS ENERGY TRANSITION

A number of business cases are described that were chosen based on probability of implementation, technological status, feedstock potential and availability, stakeholder interest (expressed in public information as well as during the PPG meetings) and replicability or development initiation power. The business cases study the use of available useable agro-industrial substrates of value for the digestion process namely poultry dropping, pig manure, animal waste (slaughterhouse) as well as residues (vinasse) of the rum distilleries and the collection of the sargassum seaweed. T[58].

2.1 Feedstock availability

Feedstock for anaerobic digestion

Feedstock supply has the task of guaranteeing sustainable biogas productivity and other adjacent benefits of anaerobic digestion (waste management, use of digestate as fertilizer). Based on the long-term plantation sugarcane production and crop cultivation expectations, Barbados agriculture will continue demanding higher quantities of fertilizer. From the agronomical point of view, cultivated soils need to be brought back to have their microorganisms that naturally carry out very important organic matter decomposition and soil amelioration. Biogas production could lead the way. Symbiotic effects of multiple source biomass input and the output of energy and bio-fertilizer should be considered by not only looking for the energy production potential but also with bio-fertilizer to assure higher agriculture productivity and lower imported inorganic fertilizers.

The business cases will focus on available useable substrates of value for the digestion process namely poultry dropping and pig manure. Collecting manure and digesting it in an anaerobic digester significantly reduces the greenhouse gas emissions originating from the manure, provides energy, reduces odour produced from the manure and also provides a nutrient-rich digestate that may be used as organic fertilizer for crop production. Most manure is digested under mesophilic, wet digestion conditions. The decomposition of cattle and pig manure starts soon after excretion, making it important to minimize the time from housing to digester to obtain the full corresponding energy and greenhouse gas abatement benefits. Livestock manure may be digested on its own, with other feedstocks and at varied scales. Not all the manure produced locally will be available to NPC. Pigs are often contained in sties/pens resulting in easier management of their manure. Cows and sheep are often left on pastures to graze and would prove difficult to collect their manure which would be subject to the elements, trampling and contamination. Chickens are raised in coups which are bedded with the substrate, retrieval of manure may be complicated

Manure can be obtained from dairy farms, beef lots, poultry and pig farms. The digestion of cattle/pig manure is an established technology and has been implemented widely all around the globe on varied scales. Digestion of poultry manure is tricky and its mono-digestion is uncommon. Poultry manure has high nitrogen content which causes the production of ammonia which inhibits the production of biogas. This can be avoided by storing pre-digestion, diluting the manure, and stripping ammonia from the liquid or semi-solid state or by co-digesting poultry manure with other feedstocks to obtain a more favourable carbon-to-nitrogen ratio.

King grass as a short-rotation energy crop is utilized in Barbados by private farmers. The opportunity of using high-yielding Napier Grass biomass opens up new possibilities for alternative energy generation. After establishing the culture, low amounts of fertilizers and pesticides are needed. Based on its high growth, its fast growth rate and its abundant forage, the high organic matter can be used for anaerobic digestion.

[58] The article is drafted by **J.H.A. van den Akker** and is available at www.ascendis.nl

Land is a key limiting resource in Barbados in general, particularly in agriculture. The Ministry of Agriculture and Food Security (MAFS) has the mandate to maximize the nation's food supply, by bringing idle lands back into production, and increasing agricultural productivity through national and household food security initiatives. Large-scale growing of crops for biomass threatens these initiatives and Barbados' self-reliance on food security goals. Any growing of king grass would have to be in a crop rotation methodology to ensure that the production of food crops as well as sugar cane can still be supported. Thus, king grass for energy offers opportunities for the financial viability of sugar farmers with additional revenue yearly outside of sugar and food crop production season.

Box 6 Biomass feedstock and methane production

	Solid content %	Biogas m^3/t solid	Methane content	Methane per ton input
King grass	16.2	400	55%	35.6
Poultry manure	39.0	500	60%	117.0
Pig manure	3.9	450	60%	10.5
Food waste	16.6	440	64%	46.6
Animal waste (guts)	11.2	400	60%	26.9
Sewage	1.3	640	50%	4.0
Vinasse	8.4	400	65%	21.9
Sargassum	6.8	270	60%	11.0

Based on *Renewable Natural Gas (Biomethane) Feedstock Potential in Barbados* (NPC) and *Bioenergy Assessment in the Caribbean; Promising Bioenergy Projects Concepts* (GFA, 2015)

Sargassum can be collected from the water using a harvesting machine or from the shore by manual labour. It is advised that preference be given to the water collection due to Sargassum beginning its decomposition process 48 hours after washing onto the beach and completing the said process within 8 to 16 days. The presence of lignin components, high salinity, and sulphide production lowers the biogas yield from seaweeds, which can be enhanced by several pre-treatment approaches such as mechanical, physical, chemical, biological, and combined pre-treatments.

There is no quantification present on how much seaweed enters a country's territorial waters. Sargassum masses generally reach Barbados around April and can last until August, though these dates may differ annually. As a result, sargassum would not be a year-round feedstock but rather seasonal. In this sense, it could be complementary to king grass as feedstock material from September-February when sargassum is not in season. Other feedstock (food waste, manure, vinasse) is, in principle, available year-round.

According to the Barbados Waste Characterization in 2015, 15,668 tons of organics were produced per month, assuming that 44% of organics is food waste. Since there is no updated figure, it is assumed that about 226 tons are being delivered and collected by the Sanitation Service Authority (SSA). This assumes that the organic waste normally delivered to the landfill is ultimately diverted to biogas facilities. This may be hard to realize in practice. Separate collection of food waste would be necessary for the recovery of energy and nutrients via anaerobic digestion but such separate food waste collection from households and businesses is not yet a local practice. In the table of Box 7, it is assumed that with economic growth (tourism) and population increase food waste potential increases to about 250 tons a day maximum.

Box 7 Methane production potential, Barbados

	feedstock ton/yr	methane yield (m^3yr)
king grass	449,195	16,009,303
food waste	91,120	4,249,208
pig manure	32,850	345,911
chicken manure	10,987	3,522
vinasse	1,547,883	33,866,131
sargassum	100,375	1,105,731

Based on *Renewable Natural Gas (Biomethane) Feedstock Potential in Barbados* (NPC) and *Bioenergy Assessment in the Caribbean. Report on Promising Bioenergy Projects Concepts* (GFA, 2015). Vinasse: see Box 17

- About 30,000 pigs were held, producing 4.5 kg of dung per pig per days, of which is 75% can be collected
- About 4.3 million chickens, producing 0.14 kg of manure per animal per day, assuming 50% of droppings can be collected
- Vinasse: 4,240 tons a day (averaged over a year) depending on ethanol production (see Box 16)
- Methane yield calculated from figures of Box 6 Sargassum: 450 tons per day harvested during 220 days (or average 275 ton/day over a year). Assumed availability of 6000 acres for king grass production (75 ton per acre; 1 harvest a year).

Crop residues have been used to return beneficial nutrients into the soil to reduce or eliminate the use of chemical fertilizers. After a harvest, the residues can be tilled into the soil, or they can be applied using a no-till method and left atop as mulch.

Crop residues are most often co-digested with livestock manure that is produced on-farm or industrial food waste. The process used for digestion in such a case is wet and the crop residues are macerated for better mixing. The most abundant crop residue in Barbados is of sugar cane.

Sugarcane industry

Sugarcane (Saccharum spp.) is a perennial grass grown primarily to produce sugar for export and rum distilleries. One ton of sugarcane produces 140 kg of straw, 280 kg of bagasse and 40 kg of filter cake[59]. In Barbados, straw is left on the field as mulch to provide nutrients to the land after a harvest. After the sugarcane has been harvested, the cut stalks are transported to the factories where they are washed and crushed to produce sugarcane juice. Bagasse is the dry, pulpy, fibrous material that remains after the sugarcane stalk has been crushed to extract its juice. Bagasse is used as a fuel within the sugar industry, about 356 TJ in 2020 (about 337,420 MMBTU; see Box 1). Bagasse can also be utilized in the production of industrial goods, such as board and paper, fuel production, and as an input in several products, including animal feed.

During the purification process, sugarcane juice is separated from solids that collect at the bottom of the storage material. This fibrous solid component is known as filter cake. Filter cake is used to fertilize soils and replenish nutrients. Following the production of sugarcane juice by milling the cane stalks, the juice is clarified, concentrated, and centrifuged to produce sugar and a syrup called molasses. Molasses is sent to be fermented in tanks where a liquid known as wine or fermentation wine is retrieved. This wine is centrifuged to recover the fermentation yeast which will be reused, and the liquid portion is sent to be distilled. As the yeast suspension is recycled, the yeast cream is diluted with water and treated with sulfuric acid for 2 hours to reduce contamination.

The distillation of wine separates the ethanol from the waste product also known as vinasse, typically about 10-15 litres of vinasse per litre of ethanol. Vinasse production is not exactly known but is estimated[60], assuming to be about 198,000-250,000 m^3. Barbados produced an estimated 14 million litres of rum in 2020[61], which means an ethanol content of 40% of about 5.5 million litres of ethanol[62]. Other sources mention higher feedstock[63]. It is assumed in the business cases that about 23 million litres of ethanol can be produced[64] yielding about 1063 m^3 of vinasse per day that can potentially be used as feedstock for biogas generation[65].

Box 8 Base data used in business case calculations

Methane - energy value	50 MJ/kg
	35 MJ/m3
Liquid fertilizer price	3 USD/m3
Solid fertilizer price	90 USD/t
Feed-in tariff, biogas	0.22 USD/kWh
Discount rate	8%
Lifetime	16 years
Emission factor grid	0.79 kgCO2/kWh (in 2015)
Natural gas	55 kgCO2/GJ

See, for example, www.engineeringtoolbox for energy value and emission factors of fuels, IPCC reports. Feed-in tariffs: BLPC/FTC websites. Fertilizer prices based on internet statistics. Emission factor grid: www.iges.co.jp

59 Renewable Natural Gas (Biomethane) Feedstock Potential in Barbados (NPC)

60 Based on NPC study *Renewable Natural Gas feedstock Potential in Barbadios* (2022) and IDB article IDB-TN-02183, *Experimental Evidence on the Use of Biomethane from Rum Distillery Waste and Sargassum Seaweed as an Alternative Fuel for Transportation in Barbados* (Henry, et.al. 2021). These amounts are a result of the ethanol production of about 15-19 million liters annually in recent (in 2020); own estimate based on above data and https://www.selinawamucii.com/insights/market/barbados/rum/

61 Own estimate, based on estimated export (about 12 million liters in 2020; https://www.selinawamucii.com/insights/market/barbados/rum/) and consumption figures.

62 Own estimates. The current sugarcane production (81,400 tons yielding about 3650 tons of molasses is not sufficient; only for about 900,000 litters of ethanol). Thus, we estimate about 18,900 tons of molasses has to be imported. For comparison: Barbados imported about 4,000 tons of molasses in 2015. Source: *Barbados in the Rum Global Value Chain* (Duke University, 2017)

63 The NPC study gives an estimate of 684 m3 per day.

64 For example, WIRC has reportedly a production capacity of about 13 million liters (https://rum.cz/galery/cam/bb/westind/index-en.htm).

65 Assuming production is about 300 days a year, so average production is 84 m^3 per day in a year. One m^3 has a mass of 5 kg, so production is 4240 tons a day, averaged over the year.

2.2 Business case 1: biogas from swine manure

Calls have been made to increase the local production of livestock to reduce the importation of foods and support local food security. This shift can see an increase in livestock inventory in Barbados. On the other hand, livestock farms face significant pressure if located in nearby residential areas due to unpleasant odours emanating from the business. Barbados has experience with handling livestock manure in AD. Barnwell farms, the largest pig farm on the island, used anaerobic digestion to digest the slurry produced by 400 pigs. The project was halted due to operational and maintenance issues. However, the experience of this system exists.

Box 9 Analysis biogas plant for pig farm

Feedstock		Input ton/day	Biogas (m^3/day)	Methane m^3 CH_4/day
Pig manure		11	197	118
Outputs				
Energy value (MJ/year)				4,241
Energy value (kWh_{th}/year)				429,986
Operating hours				7,884
Energy produced (kWh_{el}/year)				
- electricty			33%	141,912
- own use			5%	7,096
Liquid fertilizer produced (m^3 per year)				10,000
Solid fertilizer (ton/year)				225
Power generation (kW)				18
Investment cost (USD)				
- substrate storage (11 ton plus 15 m^3 spilling water)				26,000
- biogester (550 m3, HRT 19 days)				61,000
- power generator and gas control				27,000
- digestate storage (750 m^3; 2 months)				15,000
	Total			129,000
Annualised investment cost (USD/year)				13,139
Operating cost (USD/year)				
- Maintenance and servicing, BGP	2% investm.			2,040
- Maintenance and servicing, power	0.012/kWh			1,703
- Staf, operators	USD 12/hr			52,416
- Staff, management				5,000
- Insurance				1,500
- bio-support serviuces				3,200
	Total			65,859
Total annual cost (USD/year)				78,998
Levelised cost per energy (USD/kWh)				0.56
Sales				
- electricity sales to the grid				29,660
-fertilizer sales				48,000
Benefits - cost				-1,338
Annual emission reduction (at 0.79 kgCO2/kWh)				112

Adapted from *Bioenergy Assessment in the Caribbean. Report on Promising Bioenergy Projects Concepts* (GFA, 2015)

The following case is adapted from a feasibility analysis, carried out by GFA (2017) with Barnwell Farms as an example. Barnwell is a large farm with about 2000-3000 animals. This amount offers avenues for the energetic and thereafter bio-fertilizer use of both resources. Box 6 gives an indication of the theoretical biogas potential based on daily production of 11 tons of pig manure, yielding 197 m^3 of biogas a day with a methane content of 60%. The gas is used in a generator (14 kW) to generate electricity. Some of the electricity is used on-site and the excess power is sold to the grid (assumed at the current feed-in tariff of USD 0.22/kWh).

After being processed inside the digester substrate could be commercialized as a liquid organic fertilizer. The solid fraction of separated fertilizer could be commercialized and due to its high solid content would even be suitable for transport over longer distances. The fertilizer is assumed to be sold to local farmers and communities. Recovery of heat and income from heat sale (or substitution) is not considered in the case.

A summary of costs and benefits is given in the table of Box 9. In this calculation example, the biodigester would yield net monetary benefits (IRR=0%), but the reader should note this will depend on several factors. Apart from the actual investment and O&M cost, the marketability of the resulting fertilizers is a very critical point for economic feasibility. If the fertilizer sale prices are lower, e.g., liquid fertilizer at USD 2 per m^3 and solid fertilizer at USD 50 per ton, the costs exceed the combined revenue, leading to a net loss of -18,000 annually. If the feed-in tariff would be raised slightly, to USD 0.24/kWh, annual sales benefits equal annual cost (IRR=8%, i.e., same as the discount rate used).

2.3 Business case 2: biogas for power production from various feedstock

Box 10 Analysis biogas plant with various feedstock for power generation

Feedstock	Input ton/day	Biogas (m^3/day)	Methane m^3 CH_4/day
King grass (average)	40.0	2,592	1,426
Poultry manure	6	1,170	702
Food leftover	0.6	44	28
Seaweed (average)	20	367	220
Total	67	4,173	2,376
Outputs			
Energy value of methane produced (MJ/day)			85,057
Energy value (kWh_{th}/year)			8,623,856
Operating hours			7,884
Energy produced (kWh_{el}/year)			
- electricty		37%	3,232,440
- own use		6%	193,946
Fertilizer is used on-site (king grass and crops)			
Power generation capacity unit (kW)			410
Investment cost (USD)			
- substrate storage (75 m^3)			100,000
- biodigester (volume 4,000 m^3, HRT, 56 days)			350,000
- power generator and gas control			410,000
- digestate storage (5,000 m^3 ; 2 months)			100,000
		Subtotal	960,000
Annualised investment cost (USD/year)			97,778
Operating cost (USD)			
- Maintenance and servicing, BGP		2% invest	11,000
- Maintenance and servicing,power		0.01/kWh	32,324
- Staf, operators		USD 12/hr	104,832
- Staff, management			15,000
- Insurance .			8,000
- sargassum feedstock and transport		28	204,400
- other feedstock and transport		16	233,600
- bio-support services			3,200
			609,156
Total annual cost (USD/year)			706,935
Levelised cost per energy (USD/kWh)			0.22
Sales			
- electricity sales to the grid			729,238
Benefits - cost			22,304
Annual emission reduction (at 0.79 kgCO2/kWh)			2,554

Adapted from *Bioenergy Assessment in the Caribbean. Report on Promising Bioenergy Projects Concepts* (GFA, 2015), using different feedstock values

The second case describes an anaerobic digestion facility on an agricultural estate that uses feedstock from several farms, food waste, sargassum and king grass. The case is modelled on the description of a biogas plant at Armagh farms (St. Philip) [66] and a chicken manure facility (St. Lucy). The business case describes the use of biogas for power generation. It is assumed that most of the produced digestate is utilized to fertilize Napier grass cultivations; therefore, no income from digestate/fertilizer sales is considered. Heat recovery for sale as heat is not considered in the case. Alternatively, the biogas could be refined to bio-methane and sold to BNOC. This option is not presented in the table as this option is the subject of business case number 3.

A larger facility than Business case 1, the facility is assumed to be situated at or near a chicken farm. Using various feedstock boosts the size of the facility, thus achieving a better economics of scale than business case 1. However, it also increases the logistic cost, in terms of the cost of cropping, harvesting and transporting the king grass from other farms. It is assumed that the king grass (20,075 tons cultivated on 268 acres) is cultivated seasonally, as is sargassum.

The figures mentioned in Box 10 are indicative only, therefore indicate the order of magnitude of benefits and costs and do not replace the analysis that needs to be done in Outputs 2.1 and 3.1 of the SMARTER project (and this applies to the other business cases as well). To determine feedstock production potential, determination of the right feedstock input mix and costs of collection and transport of feedstock would need to be determined in a detailed feasibility study.

The cost of harvesting and transporting the seaweed is a great unknown; USD 28 per ton is assumed here (and USD 16 per ton for other feedstock. If the sargassum cost is USD 18 per ton, the calculation example gives a positive result (USD 24.500; IRR=11%).

With the same feedstock cost, but a higher feed-in tariff (of USD 0.24/kWh) the result (benefits-costs) is positive (USD 22,300; IRR =10%).

[66] Described in *Bioenergy Assessment in the Caribbean. Report on Promising Bioenergy Projects Concepts* (GFA, 2015). The Armag Farms and Armag Manufacturing Ltd. sell under the brand “Sunbury Harvest”. Products are convenient foods based on sweet potato (100 acres at Armag), corn, cassava, breadfruit

2.4 Business case 3: biogas production to feed into the natural gas network

The third business case adds two more players, the rum distilleries and the natural gas company BNOC. Rum distilleries in Barbados produce substantial amounts of vinasse, also known as 'spent wash' (organically highly contaminated wastewater from the distillation process). Besides high energy content, the vinasse contains a high concentration of nutrients (especially potassium) which potentially could be used for fertilizing issues in case of its anaerobic treatment.

The island of Barbados has a comparatively huge natural gas grid sourced by domestic gas. In line with the '100% RE goal' of the country's National Energy Policy, NPC/BNOC has an active interest in bio-methane production[67] to be fed into its national grid and is seen as a major partner (co-financier) in this business case. It drafted a 2018 Request for Proposals for the Services for the designing, building and commissioning of a Biomethane Facility at the BNOC Natural Gas Plant, Woodbourne, St. Philip, Barbados. The facility should be able to supply a maximum of 700,000 ft^3 of bio-methane to flow into the natural gas system via the pipeline at Woodbourne.

Business case 3 is modelled around this idea of producing 700 Mft^3 of bio-methane using cases described in the GFA and other studies as the source for input data on production and cost[68]. A daily amount of substrate is provided (about 886 tons a day) consisting of a mixture of king grass, slaughterhouse waste, food waste, vinasse, pig manure and sargassum seaweed. All values are empirical and should be checked on feedstock availability and characteristics to determine an adequate mix of substrates. The digestate can be marketed as a valuable liquid fertilizer (to be used on farms in the proximity of the facility) and the solid fraction of separated fertilizer could be commercialized and due to its high solid content would be suitable for transport over longer distances. It will always be vital to carry out a thorough laboratory analysis of feedstock before and after pre-treatment to find the right mix and dosage for each plant and the contents of the fertilizer.

In the example of Box 11 the biogas produced would be about 40,600 m^3 a day. There are several techniques for biogas upgrading available on the market at different development stages. Four of them are well-established on the market: membrane separation, water scrubbing, chemical absorption and pressure swing adsorption (that together have 85% of the biogas-to-methane upgrading market[69].

Under the assumptions of Box 11, the cost of the bio-methane produced would be about USD 28/GJ. This is slightly higher than the 2020 natural gas sales prices (residential sector, USD 20.0/GJ; commercial: USD 17.43 GJ. However, these prices are based on the cost of LNG import which was around USD 11/GJ before 2020[70]. In 2021, international market prices of LNG have been going up.

Biomethane needs to become commercially available and then rapidly scaled up to realize its full potential. Besides technical innovations, this requires that stakeholders along the value chain are incentivized to produce and trade the feedstock to allow for the deployment of biomethane in the most optimal way. The applied value to energy crops allows farmers to deploy sequential cropping with monetary benefits to their operations and environmental benefits relating to

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67 BNOC has commissioned the study on *Renewable Natural Gas (Biomethane) Feedstock Potential in Barbados* (NPC-BNOC)

68 *Bioenergy Assessment in the Caribbean* (GFA, 2015), cases Armagh Farms (Barbados) and Antigua Distelleries (Antigua and Barbuda), the latter using a mix of vinasse, king grass and other feedstock. *Biogas-to-biomethane upgrading: A comparative review and assessment in a life cycle perspective,* by Ardolino, F. et.al. in Renewable and Sustainable Energy Reviews, Vol. 139, April 2021, 110588, and *Techno-Economic Assessment of Biological Biogas Upgrading Based on Danish Biogas Plants,* by N. Lawson et.al, in Energies 2021, 14, 8252.

69 See article by F. Ardolini et.al. (2021)

70 Based on *Unveiling the Natuiral Gas Opportunity in the Caribbean,* R. Yépez, F. Anaya, IDB (2019) giving prices of LNG for Barbados of USD 9.7-12.7/MMBTU (plus transport USD 0.37/MMBTU). US LNG export prices stood at USD 15.59/GJ in August 2022. Thanks to natural shortage and supply issues in Europe, the global LNG benchmark price amounted to USD 42.35/GJ. Sources: http://www.eia.gov/dnav/ng/hist/n9133us3m.htm, and *Energy Prices in Latin America and the Caribbean, Annual Report 2021,* World Bank/OLADE

Box 11 Analysis of a biogas plant with various feedstock for bio-methane production

Feedstock		Input ton/day	Biogas (m^3/day)
Vinasse		550	18,513
King grass		150	9,720
Food waste		110	8,015
Animal waste		16	717
Seaweed		160	2,938
Pig manure		40	702
	Total	1026	40,604
Outputs			
Upgraded gas production (m^3 of CH_4 per day)			20,830
Gas production per year (m^3)			7,602,978
Energy value (GJ per year)			272,187
Liquid fertilizer produced (m^3 per year)			220,000
Solid fertilizer (ton/year)			25,000
Investment cost (USD)			
- substrate storage (880 t/d)			1,800,000
- biodigesters (34000 m3, HRT 47 days)			3,000,000
- digestate storage			1,500,000
- upgrading unit			4,440,000
- planning, permits, infrastrurcm commission and other cost			3,225,000
		Total	13,965,000
Annualised investment cost			1,422,366
Operating cost (USD/year)			
- O&M, BGP		2% investm.	252,000
- O&M upgrading unit			1,010,000
- sargassum/king grass supply		USD 28/t	3,168,200
- other feedstock supply		USD 16/t	4,088,000
- digestate separation			62,000
- staff cost			168960
- sales of fertilizer			-2,660,000
		Total	6,089,160
Total annual net cost (USD/year)			7,511,526
Levelised net cost per energy (USD/GJ)			28
Annual emission reduction (55 $kgCO_2$/GJ)			14970

Adapted from *Bioenergy Assessment in the Caribbean. Report on Promising Bioenergy Projects Concepts* (GFA, 2015); *Renewable Natural Gas (Biomethane) Feedstock Potential in Barbados* (NPC), and *Biogas-to-biomethane* upgrading: A comparative review and assessment in a life cycle perspective, by Ardolino, F. et.al. in Renewable and Sustainable Energy Reviews, Vol. 139, April 2021.

soil quality and biodiversity. The digestate produced from anaerobic digestion brought back to the agricultural soils allows nutrients from energy crops to be recycled back to the farmland. This concept. would interconnect many stakeholders

An interesting question is how much of the methane needs of NPC-BNOC could be supplied by bio-methane instead of mineral natural gas. Box 7 provides an estimate of feedstock availability and methane potential, which is in the order of 29 million m^3 a year (or 79,400 m^3 of bio-methane a day). Not all of the feedstock potential will be available due to loss factors such as transportation losses, environmental and land-use issues, spills, as well as alternative uses of feedstock for power generation (see the first two business cases) and non-energy purposes.

Natural gas demand was 367,000 GJ in 2020 (see Box 1), that is, 28,727 m^3 per day. To supply future demand with bio-methane (100% RE), NPC estimates bio-methane needs at 39,500 m^3 per day. The Box CCVC indicates how potentially this bio-methane can be produced from .vinasse, food waste, pig slurry, slaughterhouse waste, year-round, and from seaweed and king grass on a seasonal basis.

Box 12 Bio-methane (renewable natural gas) needs and feedstock potential

Feedstock	Est. potential ton/day	Input ton/day	Biogas (m^3/day)
Vinasse	4241	820	27,601
King grass	1231	550	35,640
Food waste	250	115	8,379
Animal waste		20	896
Seaweed	275	200	3,672
Pig manure	90	50	878
Total		1755	77,066
Output			
Upgraded gas production (m^3 CH_4/day)			39,535

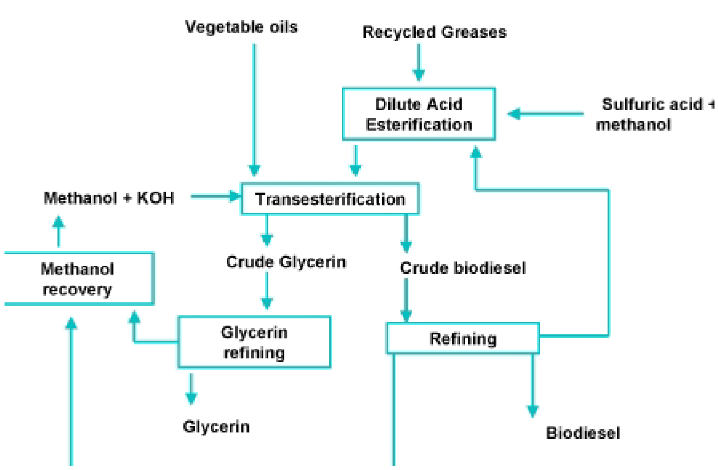
2.5 Business case 4: biodiesel production

Two following two cases will look at the two different alternatives that generate biofuels that are relevant for Barbados: biodiesel to reduce the fossil fuel content of the diesel fleet bioethanol to replace gasoline.

biodiesel can be mixed with mineral diesel and used in diesel engines without the need for thorough and costly vehicle modifications and adaptations. Blends with concentrations between 6% to 20% can be used for many applications using mineral diesel, with little or no equipment modifications, and pure biodiesel (B100) can be used provided appropriate precautions are taken. In this business the focus is on B20, representing a good balance between cost, emissions, and material compatibility, and explains that, based on user experience, no apparent vehicle modifications are necessary for the use of a 20% biodiesel blend. Trucks, tanks, pumps, and blend facilities can be used for B20 and no changes are required at the gas stations in the case of B20 supply, allowing the use of the same infrastructure for mineral diesel supply.

Currently, the Barbados National Terminal Company (BNTC) is preparing a pilot with the aim of testing imported B100 and B10 fuels for marketing to the general public[71]. The results will determine the strategy for converting the entire market to an appropriate biodiesel blend in close discussion with the main stakeholders (e.g., BLPC and the major oil distributors Sol, Rubis and Harville. The limited infrastructure at petrol stations and dispensing facilities eliminates the possibility of a partial introduction or having ULSD "side by side" with a B10 or a B20. Hence there will be a need for an "all or nothing" changeover.

Box 13 Biodiesel production process



Biodiesel in essence is a plant or animal based oil without glycerine molecules. In transesterification, the vegetable oil is mixed with an alcohol (methanol) and under presence of a catalyst (KOH or NaOH) the glycerin molecule is separated from the fatty acids in the vegetable oil, producing glycerol and a methylester (crude biodiesel) that is further refined to produce biodiesel with the same characteristics as mineral diesel.

See: http://www1.eere.energy.gov/biomass/abcs_biofuels.html and *Building Energy Independence in Small Island Developing States: the Role of Biodiesel,* E. Smit and B. Doberstein, 1st International Conference on Governance for Sustainable Development of Caribbean Small Island Developing States. Curaçao

The case looks at the impacts and feedstock options for B20 usage. To have the possibility of meeting the B10, the bio-diesel either has to be directly imported or through domestic production for which it will have to install a biodiesel production plant. The feedstock for domestic production is available in the form of used cooking oil (UCO) or from vegetable oil, such as soybean oil. The soybean oil feedstock either has to be produced on the island or imported.

The BNTC pilot will use biodiesel locally manufactured from UCO supplied at the amount of about 12,000 litres a month. The company Native Sun NRG collects waste vegetable oil from restaurants and hotels that are then processed at the facility in Edgehill, St. Thomas.

The UCO feedstock is higher, maybe about 1,150,000 litres a year. The business case described here looks at the feasibility of setting up a facility that could produce 1000 tons of bio-diesel annually from a similar amount of waste vegetable oil.

It is assumed here that UCO is available at USD 300 per ton. At this price and under

[71] The cost of setting up the pump and blending infrastructure for dispending biodiesel at the loading rack is an estimated USD 180,000. The biodiesel B100 and B10 will be tested in a cross-section of vehicles (NPC/BNOC/BNTC diesel fleet, diesel generators, buses, fishing vessels, construction and delivery vehicles.

other assumptions in Box 14, the biodiesel could be produced at around USD 0.60 per litre. Waste vegetable oil has the advantage that it is much cheaper than using fresh vegetable oil. If imported soybean oil would be used as feedstock (at about USD 1.11 per kg), the price of the soydiesel would be USD 1.59 per litre.

Box 14 Analysis biodiesel production from used cooking oil

	Unit cost	Units	Cost
Feedstock	(USD/unit)		(USD)
- waste/cooking oil (tons)	300	1010	303,000
- methanol (tons)	526	130	68,380
- chemical (ton)	1000	8.755	8,755
- water (m3)	2.1	12,000	25,200
- power (kWh)	0.305	150,000	45,750
- labour (person.months)	1920	24	46,080
- other	10	3,000	30,000
			527,165
Output	Price	Units	Sales
	(USD/unit)		(USD)
- biodiesel litre)		870,000	
- glycerol (litre)	0.579	79,302	45,908
Investment cost			
- equipment			408,300
- other cost, contingency			102,075
Total			510,375
- annualised cost			57,661
Total net annual cost			538,917
Levelised cost per litre (USD/litre)			0.62
Levelised cost of energy			
Annual emission reduction (at 2.8 kgCO2 per litre of diesel)			2,436

Adapted from *Cost Analysis for Biodiesel Production from Waste Cooking Oil Plant in Egypt,* A. Al-Gharbawy, in: Smart Grid (January 2017), *Comparative Technoeconomic Analysis of Using Waste and Virgin Cooking Oils for Biodiesel Production,* E.Sakkari et.al. in: Bioenergy and Biofuels, Frontiers in Energy Research, 2020; *Building Energy Independence in Small Island Developing States: the Role of Biodiesel,* by E. Smit and B. Doberstein (2011)

The amount of UCO-based biodiesel produced is 870,000 litres, about 5.5% of the need for biodiesel in the B20 scenario. Currently, the demand for diesel is about 40,000 barrels a month. Thus, demand for B20 would be 20%, that is 1,272,000 litres a month or 15.26 million litres of biodiesel annually. Thus, the remaining biodiesel demand of 13.39 million litres would either have to be imported or produced locally in a large biodiesel production facility, or a combination of these two options. At the August 2022 price of biodiesel in the USA (USD 1.8 per litre), the import bill would be USD 25.9 million annually. The biodiesel facility would need to import the soybean oil feedstock[72]. At USD 1.11 per kg, the cost of biodiesel is about USD 1.5 per litre, implicating an import bill of about USD 22.9 million.

Adding the amounts of UCO-based biodiesel plus biodiesel and/or local production with imported feedstock gives a cost of USD 23.4 to 26.5 million annually. These amounts have to be compared with the alternative bill of importing mineral diesel oil; at the May 2022 diesel price of USD 0.9 per litre, the import of 15.26 million litres of mineral diesel would cost about USD 13.7 million.

Not included in the cost estimate is the need for storage facilities. At the amounts mentioned in the business case, a storage capacity of 3 million litres is needed (to meet the country's demand for B10 for 3 months).

To produce the 13.39 million litres of soybean oil locally would be cheaper than importing but require the cultivation of 64 million tons of soybean for which the land requirement is 24,000 hectares, an area much larger than available in practical terms, not larger than About 1,800-2,400 hectares (the land surface area of Barbados is 43,900 hectares). Given the low share of local production in the soybean oil demand, it is likely to be more economic to import the feedstock. An interesting alternative mooted is leasing land in a neighbouring country (e.g., Guyana) and producing and processing the feedstock there for delivery to Barbados[73].

Introducing B100 (total replacement of diesel over time) would bring new cost items, such as the gradual replacement of diesel vehicle fleet for vehicles adapted to the use of pure biodiesel. Additionally, gas stations will require an adaptation

[72] For comparison: diesel prices were USD 0.80 per liter in 2020 and USD 1.1 per liter in May 2022 in Europe and USD 0.50 and USD 0.90 in USA respectively. The diesel price in Barbados was about USD 1.5 per liter. Biodiesel prices were USD1.5 per liter in 2020 and USD 1.8 per liter in May 2022 in Europe and USD 1.3 and US1.7 in USA respectively. Source: IEA website; Energy Bulletin 2021 (Energy Division, MEB)

[73] Figures: own elaboration based on data provided in *Feasibility Assessment of Including Liquid Biofuels in the Transport Sector in the Context of Energy Transition and Carbon Neutrality in Barbados,* draft report (NPC)

of their infrastructure (tanks and pumps) to provide B100 to end customers, ensuring the use of ethanol-compatible materials.

2.6 Business case 5: ethanol production and bagasse power generation

Sugarcane production in Barbados is divided between government-managed farms, overseen by the BAMC, and independent farms managed by landowners. The government gained control of approximately 40-60% of sugarcane fields in the early 1990s when declining sugar prices and rising costs created high levels of debt that many farmers were unable to repay. To help maintain the industry, the government seized control and managed the indebted farmlands. The Barbados Sugar Industries Limited (BSIL), a holding company, represents the interests of the independent sugarcane producers in the country. Harvested sugarcane is crushed to produce three by-products: bagasse, sugar, and molasses. As a rule of thumb, a ton of sugarcane gives about 140 kg of straw, 40 kg of cake and 280 kg of bagasse, yielding.90 kg of sugar[74] and 45 kg of molasses and 11 litres of ethanol. In 2020, production was about 81,000 tons of sugarcane (produced on about 2,160 hectares) yielding about 7,200 tons of sugar. Most sugarcane is sold to the government-managed Port Vale plant for processing. e into raw brown sugar, which is exported in bulk to Europe.

Rum manufacturing follows the production of molasses[75]. In 2020, Barbados exported about 12 million litres of rum (at a value of about USD 80 million[76]). Rum is produced by three distilleries, West Indies Rum Distilleries (WIRD), Mount Gay, Foursquare and St. Nicholas Abbey. The amount of molasses produced is not sufficient feedstock for the rum distilleries that therefore import molasses from neighbouring countries, such as Guyana[77]. Some rum companies in the country are attempting to overcome the sugar industry problems by producing rum directly from sugarcane juice, leapfrogging the capital-intensive sugar manufacturing stage of the value chain that is needed to obtain molasses. In this case, the entire cane is fermented and a mill can produce about 80 litres of ethanol and no sugar. Sugar and sugarcane production has been declining over the past decades[78]. Thus, the nation is hoping to shift away from bulk sugar exports toward packaged sugar in an attempt to upgrade to higher-value activities.

The ethanol production gives on average 13 litres (or 65 tons) of vinasse residue. The vinasse is an important potential feedstock for local bio-methane production, as described in Business case 4[79]. Current production is about 205-585 m^3 per day (averaged over a year)[80].

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74 Figures mentioned in *Renewable Natural Gas (Biomethane) Feedstock Potential in Barbados* (NPC). See also https://indianexpress.com/article/explained/explained-why-govt-encouraging-ethanol-production-sugar-mills-molasses-6106610/

75 Water and yeast are added to the molasses, and the mixture is then fermented. After fermentation of the molasses, the liquid undergoes a process of distillation before a rest period in barrels, known as repose. The distillation process is straightforward—fermented liquid is heated in sealed vats, also known as stills, to a temperature of 78.3ºC, which causes the alcohols to evaporate. Evaporated alcohol, once re-condensed, is then collected as a raw spirit, which is then aged in charred oak barrels. Aging time varies among producers and can range from no time to decades. After aging, rum can be passed through a charcoal filter to give it a clear appearance, making light rum. Alternatively, it can be left as is, resulting in a different flavor profile and a darker rum. Source: *Barbados in the Rum Global Value Chain,* by D. Hamrick and K. Fernandez (Duke University, 2017)

76 https://barbadostoday.bb/2020/01/17/rum-makers-report-rising-sales/

77 A back-of-the-envelope calculation shows that with Barbados producing about 5.7 million liters of ethanol in 2020 (for export and local consumption of about 2 million liters) and assuming that the 81,000 tons of sugarcane processing yielded 3650 tons of molasses, the difference of about 19,560 tons of molasses had to be imported.

78 In 2000 Barbados produced half a million tons of sugarcane, which had dropped to 160,000 tons of sugarcane (of which 44% by BAMC and the rest on about 30 smaller farms), while also productivity dropped from 61 ton/ha in 2000 to about 48 ton/ha in 2015 37,5 t/ha in 2020. It is interesting to note that with the declining sugarcane production, also the use of bagasse for energy (heat and electricity) production declined from 1.38 TJ in 2000 to 0.46 TJ in 2015 and 0.39 TJ in 2020. Source: OLADE

79 The other residues, such as sugarcane straw, bagasse, nor filter cake are not seen as viable option for anaerobic digestion the short term due to competing uses of these feedstock.

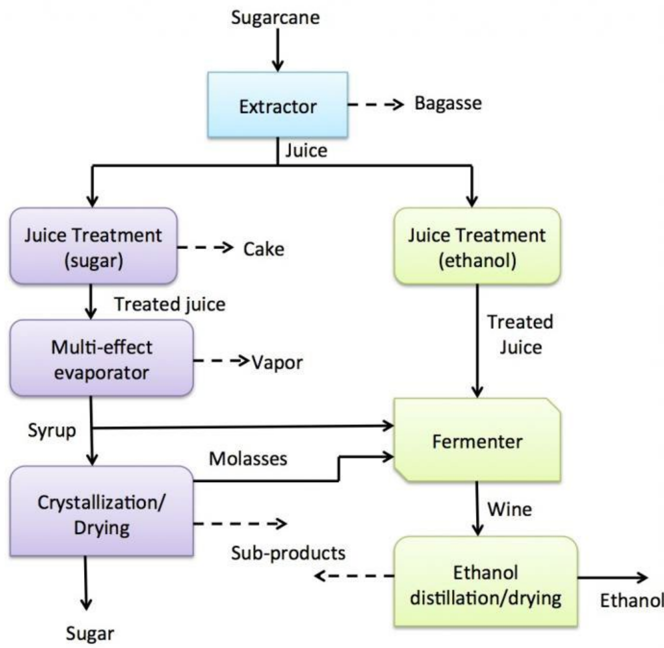
80 Based on the figure of 5.67 million liters of ethanol production (in 2020, see footnote) the vinasse production equaled about 74,000 m3. The IDB report *Experimental Evidence on the Use of Biomethane from Rum Distillery Waste and Sargassum Seaweed as an Alternative Fuel for Transportation in Barbados* (Legena Henry, et.al.) gives estimates of 213,600 m^3 (60 m^3/day during 160 days by Four-Square Rum and 600 m^3 a day during 330 days by West Indies distilleries.

The impact on the wear of vehicle metallic components due to the use of a gasoline mixture with up to 10% ethanol is regarded as irrelevant if compared to pure gasoline. With the use of mixtures above 10% of ethanol, the vehicles need changes in the combustion cycle.

A plan for the possible use of ethanol would start with a change of pure gasoline to E10 (gasoline with 10% ethanol), which is described as 'scenario 1' in the NPC-commissioned draft *Feasibility Assessment of Including Liquid Biofuels in the Transport Sector in the Context of Energy Transition and Carbon Neutrality in Barbados.*

Assuming a gasoline demand of 110 million litres[81], the E10 demand will be 16.8 million litres annually[82]. Adding the production for non-energy uses (rum) of an estimated 7 million litres of ethanol annually, total production in the case described here will need to be 21.42 million annually (see Box 16). It is assumed that all the ethanol is locally produced from 120,000 tons of sugarcane for 49.1 kilotons of molasses imports) while another 120,000 tons are specifically grown for ethanol and processed in a new facility (where 1 ton of sugarcane can produce 80 litres of ethanol).

Box 15 Sugarcane processing into ethanol and sugar



https://www.e-education.psu.edu/egee439/node/646

Box 16 Production of ethanol in Barbados for energy and non-energy purposes and use of bagasse

		Dedicated local ethanol prod.	Ethanol and sugar production			TOTAL
			Local cane	Import	Subtotal	
sugarcane	ton/yr	120,000	100,000		100,000	220,000
ethanol	litre/yr	9,600,000	1,100,000		13,113,584	23,813,584
bagasse	ton/yr		28,000		28,000	
molasses	ton/year		4,500	49,146	53,646	53,646
vinasse	ton/yr	624,000	71,500		852,383	1,547,883
land use	hectares	1,846	1,538		1,538	3,385
	acres	4,560	3,800		3,800	8,360

Assumed productivity is 65 ton of sugarcane per hectare.
Annual demand is based on E10 demand (16.81 million liters annually) for rum production (7 million liters annually).
The resulting production of the distillation residue wastewater (vinasse) of 1.39 million tons a year, is used as input data in Box ….
Assumption is that 1 liters of ethanol production generate 13 liters of vinasse (1 liter weighs 5 kilo).
Data are adapted and combined from various sources,. including the NPC feedstock assessment and biofuels study

Ethanol's chemical characteristics complicate fuel supply logistics since ethanol cannot be used in the same pipelines with oil derivatives, or stored in the same tanks[83].

[81] Import in Barbados were 116.3 million (2019), 102.8 million (2020) and 101.2 million (2021)

[82] This is more than 10% of gasoline substitution due to energy density differences (gasoline: 32.2 MJ/liter; ethanol: 21.1 MJ/liter)

[83] A technical analysis of the existing fuel storage system in Barbados must be conducted to evaluate the possibility of converting the

From the example in Box 17 follows that the E10 production cost will be in the order of USD 0.76 per litre of ethanol. For comparison, the price of gasoline traded in the period Nov'21-Nov'22 was about USD 0.66 for gasoline and USD 0.68 for ethanol[84]. A litre of gasoline was sold for USD 1.895 in 2021 at Barbadian filling stations, reflecting the cost of production, distribution and margin as well as taxes (discounting the taxes the value is USD 0.863 per litre).

Box 17 Production costs and benefits of using E10 and bagasse power generation

Inputs		.
E10 demand		16,813,584
- ethanol fgrom local sugarcane feedstock		9,600,818
- ethanol from imported molasses		7,212,766
Molasses imports (ton/yr)		29,507
Sugarcane production (ton/yr)		129,000
Storage capacity needed (litres for 2 months))		2,100,000
Investment cost		
Storage capacity needed (3.5 million litres)		1,375,000
Land preparation and cane cultivation		4,500,000
New distillery (9.6 million litres)		12,300,000
Adaption of filling stations (42 station)		0
	Total	18,175,000
Annualised investment cost		1,851,164
Annual cost		
- molasses imports		9,147,098
- O&M cost, cane production, distillery	10%	1,817,500
	Total	10,964,598
Total annual cost		12,815,762
Production cost per litre		0.76222668
Emissions avoided (at tCO2 per litre)		38,517

	Current	**Scenario**	
Sugarcane production	81,064	100,000	tons/yr
Bagasse production	22,698	28,000	ton
Energy value for CHP	264,204	325,920	GJ/yr
Losses (15%)	31,548	13,580	MWh/yr
Power production (40)	29,356	36,213	MWh/yr
Heat prod. (45%, own use)	33,025	40,740	MWh
Operation		4,320	hr
Total power	6.8	8.4	MW
- capacity, own use	2.0	5.9	MW
Electricty, own use	8817	10,876	MWh/yr
Electr sales		25,337	MWh/yr
Value, energy sales (at USD 0.15/kWh)		2,392,753	USD
Connection cost (substation, etc.)		750,000	USD
Avoided GHG emissions (0.79 tCO2/MWh)		20,016	tCO2/yr

The storage system and distillery type and costs considered are based on a Brazilian example referenced in the NPC biofuels study. See CGEE. *Bioetanol Combustível: Uma Oportunidade para o Brasil. 1. ed. Brasíli*a (CGEE, 2009). The ethanol input data (locally produced and from imported molasse taken from Box 28

The bagasse produced in sugarcane production is used within the sugarcane sector on-site in combined heat-power schemes (cogeneration). Currently, the excess power produced is not delivered to the grid as this would need compliance with the grid code and additional investment (e.g., in a substation). The capacity installed currently can deliver 5-6 MW but only 1.5-2 MW is used for on-site power consumption. However, in the past, a total of up to 10 MW of power capacity was installed at sugarcane processing facilities. It is assumed in the calculation example of Box 18 that the bagasse produced in the cultivation of 100,000 tons of cane per year, is utilized for power generation with the excess electric energy (an estimated 25.3 GWh per year) sold to BLPC.

Other scenarios in the NPC biofuels study consider a more aggressive penetration of ethanol in the vehicle park by a) replacing gasoline vehicles with flex-fuel vehicles (that can run on pure ethanol). Having the whole vehicle park in flex-fuel mode would require gas stations (tanks and pumps) to adapt their storage and pumping infrastructure ensuring the

system to ethanol usage, similar to the biodiesel. To mix the E10 with gasoline, a method known as splash blending to mix the fuels, mixing made inside the tank truck compartment itself through its movement. The installation of the ethanol distribution center incorporated into the container port and the fuel mixing being done directly in the truck leaves the supply chain logistics leaner and requiring fewer investment. Mixing higher percentages will adaptation in the distribution system (storage and filling stations) and the combustion engine of the vehicles (see next section of this Annex)

84 See https://tradingeconomics.com/commodity/ethanol. Barbados prices based on Energy Bulletin (Energy Division, 2021)

Box 18 Annual cost and benefits of substation of gasoline and diesel by ethanol E10 and biodiesel B20

Biodiesel B20 cost (in USD)	UCO	Other	Total
- imported biodiesel and produced from UCO	577,970	10,462,766	11,040,736
- or, produced from UCO and imported soybear	577,970	10,751,580	11,329,550
(in USD/litre)	0.9	1.1	1.5
Diesel imports avoided	6,868,800	8,395,200	11,448,000
Avoided GHG emissions (tCO2 per year)	21,370		
E10 ethanol costs (in USD)			
- cost of local E10 production			12,815,762
Import avoided		.	
- of ethanol (at USD 0.68 per litre, 2022 prices)			11,416,357
- or, of gasoline (at USD 0.66 per litre, 2022 prices)			7,207,398
Avoided GHG emissions E10 (tCO2 per year)	38,517		

use of ethanol-compatible materials[85]. Scenario 3 of the NPC study considers a distillery capacity of about 27 million litres. The production cost, quoted in the NPC study is an estimated USD 23.3 million which is ethanol production at USD 0.89 per liter. This does not include the cost of importing flex-fuel vehicles.

Box 18 gives a summary of the annual cost implications of the nationwide introduction of B20 biodiesel and E10 ethanol in the transport fuel supply system

2.7 Business case 6: vehicles running on bio-CNG

Apart from powering vehicles with biodiesel or ethanol, a third bioenergy option is powering them by bio-CNG (compressed natural gas), produced in anaerobic digestion. Biomethane, which consists of the same molecule as natural gas, namely CH_4 or methane, can be compressed in a CNG installation to be used as a transport fuel. Cars can be converted from gasoline consists which requires a CNG kit and a refueling cylinder. The kit consists of high-pressure regulators (which reduce and regulate the pressure of the fuel exiting the tank from about 200 bars to the 10 bars required by the engine's fuel injection system), a gas filter, and natural gas sensors (which monitor the pressure of the gas). The technology as such is a mature, commercial, technology and available in many countries. Worldwide, about 28.54 million vehicles were fueled by CNG which was made available in over 33,000 filling stations in 2019[86].

The University of West Indies (UWI) is carrying out research on using Sargassum seaweed mixed with vinasse from ethanol producers as feedstock for bio-digestors[87]. After experimenting with various Sargassum-vinasse ratios, as a next step, UWI will carry out a pilot with two bio-digesters (15 m^3 each) and initially two vehicles. The cost of the pilot is an estimated USD 200,000[88].

For bio-CNG to be introduced on a more commercial, this section describes the business case of 3,000 vehicles powered by CNG produced in anaerobic digestion. It is assumed in the case described that the biogas is produced separately in biodigesters fed by vinasse and sargassum feedstock with the purpose of producing bio-CNG to make clear the production and cost numbers behind the case. Alternatively, the biodigesters can feed the already existing infrastructure of a nationwide natural gas grid that can then be delivered to the filling stations or the bio-CNG is simply produced in the larger facility as described in Business case 3 on bio-methane.

At an average consumption of 885 litres of gasoline per year, a car user would have spent USD 1,677 on gasoline per year (at the 2021 retail price of USD 1.895 per litre)

85 Adapting the 42 filling stations in Barbados would will cost about USD 1.9 million

86 http://www.iangv.org/current-ngv-stats/

87 See website http:// rumandsargassum.com and the IDB technical report *Experimental Evidence on the Use of Biomethane from Rum Distillery Waste and Sargassum Seaweed as an Alternative Fuel for Transportation in Barbados*, IDB-TN-02183 by L. Henry et.al. (2021)

88 With annual cost of about USD 170,000. Data provided by UWI, L. Henry, p.c.

Box 19 Analysis of bio-CNG production for fueling 3,000 vehicles

		Input	Biogas
Feedstock		*ton/day*	*(m^3/day)*
Vinasse		432	14,541.1
Seaweed		112.5	2,065.5
	Total	544.5	11,918.5
Outputs			
Upgraded gas production (m^3 of CH_4 per day)			6,114
Gas production per year (m^3)			2,231,687
Energy value (GJ per year)			85,474
Liquid fertilizer produced (m^3 per year)			64,576
Solid fertilizer (ton/year)			7,338
Investment cost (USD)			
- substrate storage (400 t/d)			50,000
- biodigester (volume 17,000 m^3, HRT, 50 days)			175,000
- digestate storage			750,000
- upgrading unit			2,220,000
- planning, permits, infrastrurcm commission and other cost			639,000
- cost of CNG retail station			2,400,000
	Total		6,234,000
Annualised investment cost			634,947
Operating cost (USD/year)			
- O&M, BGP	2% investm.		39,000
- O&M upgrading unit			505,000
- sargassum/king grass supply	USD 28/t		1,149,750
- other feedstock supply	USD 16/t		657,000
- digestate separation			31,000
- staff cost+services			90,000
- sales of fertilizer			-780,785
- O&M, filling station			168000
	Total		1,858,965
Total annual net cost (USD/year)			2,493,912
Levelised net cost per energy (USD/GJ)			29.2
Cost per m3			1.118
Annual emission reduction (69 $kgCO_2$/GJ)			5898

Cost of biodigester and O&M is derived from same sources as Business case 3. Data on cost of CNG compression and filling stations derived from figures mentioned in *Perspectives of Biogas Conversion into Bio-CNG for Automobile Fuel in Bangladesh,* M.S. Shah, et.al. (2020) in Hindawi Journal of Renewable Energy (August 2017) and *Costs Associated With Compressed Natural Gas Vehicle Fueling Infrastructure,* by M. Smith (US Department of Energy) and J. Gonzalez (NREL), 2014. The cost of a medium station (supplying 500-800 gallons of gas equivalent a day) is about USD 800,000. Tio supply the annual need of the 3000 CNG vehicles (with a need of about 1900 gge a day), three such stations are assumed in the calculations. The gas demand is based on the consumption if 885 liters of gasoline per vehicles per year bout 116,200 registered vehicles (*Energy Bulletins*, MEB).
Retailer prices in 2021 were:
- Gasoline: USD 1.895 per liter (without tax: USD 0.8634 per liter)
- Diesel: USD 1.52 per liter (without tax: USD 0.834 per liter)

In the case described in Box 19, the cost of the bio-CNG produced is USD 29.2 per GJ (or 1.118 per m^3). If the CNG would be taxed as diesel, the cost of 1 m^3 of CNG would be USD 1.8959. Converted to CNG, the car user would have used the equivalent of 744 m^3 of CNG (per year) with an annual cost of USD 1410 per year. Thus the car owner would save about USD 226.41 per year (under all the assumptions mentioned). At an average cost of a CNG kit of about USD 750, this implies that the car owner would see his investment in a CNG installation paid back in about three years.

2.8 Environmental aspects of anaerobic digestion

The business cases study the use of available useable agro-industrial substrates of value for the digestion process namely poultry dropping, pig manure, animal waste (slaughterhouse) as well as residues (vinasse) of the rum distilleries. The vinasse and further organic wastes treatment in a biogas plant have a couple of direct and indirect benefits for the environment and hygiene. In the case of vinasse, the vinasse digestion will be the protection of the water resources as after digestion the vinasse will be used as an efficient fertilizer which does not cause plant damage when released into the sea. Marine pollution is further diminished by finding a use for the collected seaweed (Sargassum).

Globally the reduction of greenhouse gas emissions, especially the direct greenhouse gases methane and nitrous oxide is important. Both are generated by normal manure storage and then emitted into the atmosphere. Methane has a 25-fold greenhouse effect compared to carbon dioxide, nitrous oxide is 300 times more strong. The anaerobic digestion in a biogas fermenter avoids the generation of nitrous oxide, which is formed especially under semi-oxigenous conditions, when nitrogen-rich substrates are degraded. The methane generation is enhanced, but in a controlled process with the utilization of the generated gas. In this way, the methane is transferred to CO_2 by a factor of 25. This carbon dioxide is climate neutral as it is generated from manure as a renewable resource.

The biogas digestion of organic wastes has several indirect and direct hygiene effects. The reduction of pathogens by the biogas process depends strongly on some technical parameters like digestion temperature level, pre-treatment, heat step in between the process, average and secure retention time, cascading and more. As named before, the process takes place in a closed tank under anoxic conditions. The easily degradable organic compounds are degraded in the process. This means that insects, rodents and other animal vectors lose their feed base and sometimes their habitat. If one of these vectors comes into a plant, it will die and will be degraded. Those are very strong indirect effects to enhance hygiene in organic waste management.

2.9 Potential of bioenergy production in Barbados' energy transition

This section provides a summary of the potential contribution to the energy system by the year 2040, if the business cases discussed in this Annex (sections G.2 to G.7) will actually be implemented within the limits posed by feedstock availability and collection (see the potential feedstock amounts provided in Box 7, in section G.1).

- Business cases 1 to 3 will be implemented twice each, so the amounts of electricity and renewable natural gas generated will double those mentioned in the Boxes will be doubled to provide
- If Business Cases 4 to 5 will implemented, these will provide sufficient amounts of biofuel to have B20 and E10 inserted in the transport fuel distribution system according to the 'all-or-nothing' principle. Business Case 6 will provide bio-CNG to power 3000 vehicles. more renewable natural gas could be provided to power more cars through the country's national gas pipeline system, but then less would be available for use in other sectors (residential, commercial, industry).
- If the business cases will be implemented as described, the bioenergy system will reach its limits in terms of domestically available feedstock. Here it should be noted that already the amounts of used cooking oil (UCO) for biodiesel production the Business case 4 already assumes that most of the biodiesel (to be able o fully supply B20 given the size of the diesel-

Box 20 Feedstock availability and potential to generate the bioenergy requirements of the business cases

	Maximum	Number	2	2	2	1	1	1
Feedstock '(in ton per year)	potential	Need	Case 1	Case 2	Case 3 *	Case 4	Case 5	Case 6
king grass	449,195	173,862		31,268	142,593			
food waste	91,120	92,418		438	91,980			
pig manure	32,850	37,413	8,213		29,200			
chicken manure	10,987	4,380		4,380				
vinasse	1,547,883	597,984			440,304			157,680
vinasse (w/o E10)	553,124	157,680						157,680
sargassum	100,375	100,163		7,300	51,800			41,063
vegetable oil for biodiesel **	1,001	7,850				7,850		
sugarcane for E10	120,000	120,000					120,000	
Land use (hectares)	5,813	4,324						
- king grass	2,428	940	Notes:					
- sugarcane for E10	1,846	1,846	* With uncertainty in sargassum collection potential, it ias assumed in Case 3 that more					
- sugarcane - other	1,538	1,538	king grass and vinasse is used as feedstock and less sargassum then described in Box 23					
Currently used (sugarcane)	2,160		** Used cooking oil potential with difference will be imported biofuel or soybean feedstock					
Available for farming	10,000		*** Potential sugarcane will be determined by land-use allocation					

powered vehicle park) either have to be imported or produced locally from imported feedstock such as soybean. The amount of vinasse produced is linked with E10 production. If it is decided not to introduce E10 in the Barbados transport fuel mix, the ethanol production will remain at current levels (mainly for sugar and rum production at current levels) and the vinasse output would one be a third only. With less vinasse, there will also be less feedstock for anaerobic digestion.
- A potential large biomass resource is the sargassum seaweed, but it is not very well known what the options for cost-effective onshore or offshore harvesting will be. The figures mentioned in this Annex G are very preliminary estimates of potential and costs.

With limited feedstock and alternative uses, competition from other renewable energy technologies (solar, wind), and choices will have to be made. The description of business cases and level of inclusion in the bioenergy production, as described in this section, does not imply a preference for certain cases over other cases, but to have a quantitative estimate of the order of magnitude of feedstock and potential bioenergy production for a range of uses.

Currently, bioenergy provides only a small part of the primary energy supply of Barbados, about 2.5%, as visualized in Box 22. The figure on the right in the box gives the energy flows in a future low-carbon scenario for the year 2040, in which:

- Despite a modest population and economic growth, the energy demand has decreased due to higher efficiency and lower energy intensity of the economy;
- Most energy resources are locally produced rather than imported;
- Almost 100% of electricity is generated by renewables, including bioenergy (from the application of Business cases 1,2 and 3)
- Significant electrification of end-use resulting in a much higher share in final energy demand (more than half).
- The amount of bioenergy has risen more than 15-fold and forms almost 20% of the energy supply.

For transport, it has been assumed that by 2040, the same amounts of biodiesel and ethanol are produced as given in **Box 21**, but as B100 and E100 usage (i.e., with fuel supply infrastructure and vehicle engines adapted to the use of pure biodiesel and bio-ethanol. These amounts can power 3,843 B100 vehicles and 4,352 E100 vehicles, assuming that all E100 and B100 are locally produced. Assuming that in 2040, 146290 vehicles will be circulating, this assumes that 92% of vehicles will be electric (in line with the high demand-high EV scenarios of the IRRP 2021) in a full net-zero carbon scenario. If the share of electric vehicles is less than either E100 or B100 needs to be imported (or more feedstock imported for local production or by fossil fuels.

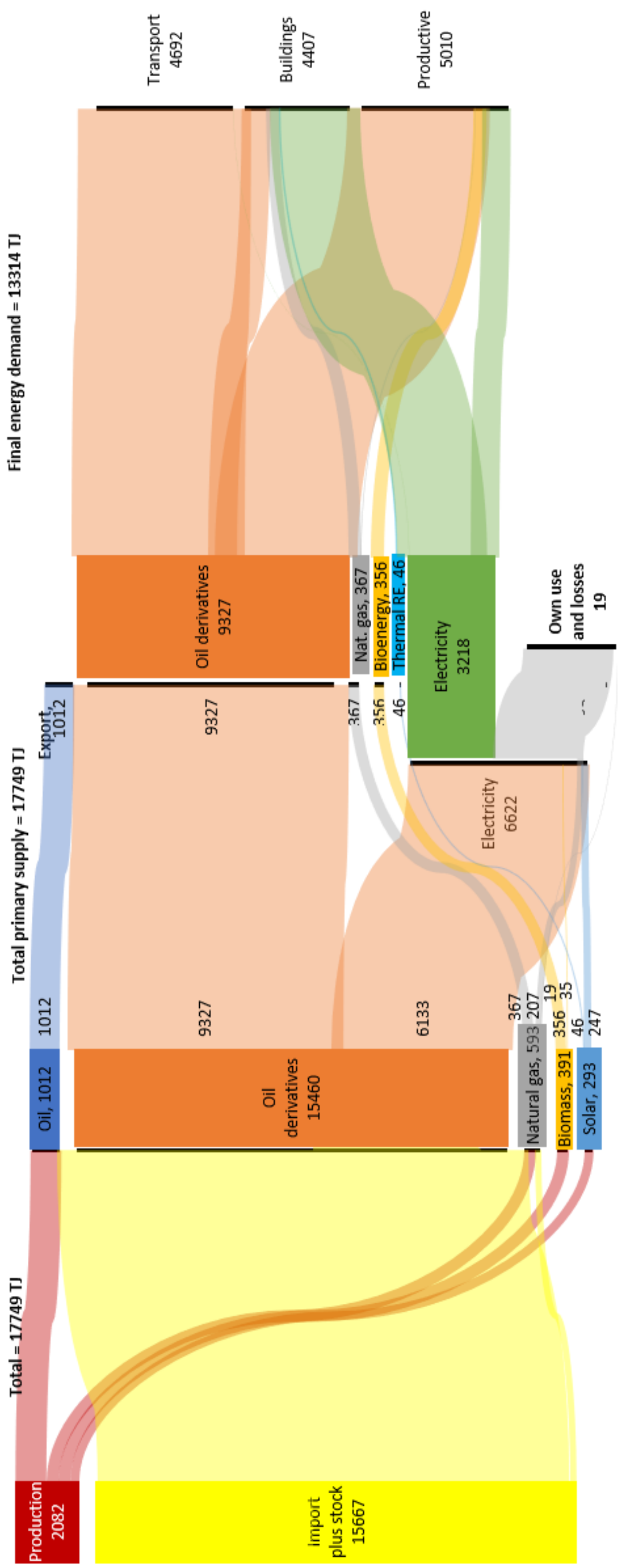
In the 2040 scenario, still, about 34% of the energy supply needs to be imported. To be 100% RE, these will need to be imported, either biofuels, green hydrogen (or derivative fuels, methanol, ammonia), or fossil fuels that have been produced with carbon collection and storage (CCS).

Box 21 Potential bioenergy production for electricity or fuel needs

Generation/conversion	*Anaerobic dig.*	*Anaerobic dig.*	*Anaerobic dig.*	*Extraction*	*Extraction*	*Fermentation*	*CHP*	*Anaerobic*	**Total**
Final energy product	*Electricity*	*Electricity*	*Bio-methane*	*Biodiesel demo*	*Biodiesel B20*	*Ethanol E10*	*bagasse*	*Bio-CNG*	
Biomass feedstock	Animal dung	Animal dung Food waste King grass Sargassum	Animal dung Food waste King grass Sargassum Vinasse	Used cooking oil (UCO)	UCO Soybean oil	Sugarcane Molasses	Sugarcane	Sargassum Vinasse	
Description case (Annex G)	Case 1	Case 2	Case 3	Case 4a	Case 4b	Case 5a	Case 5b	Case 6	
Number	2	2	2	1	1	1	1	1	
Power (kW)	36	820					2,517.6		**3,373.6**
Electric energy (kWh/year)	283,824	17,247,712					25,337,181		**42,868,718**
Fuel (m3, gas or litre, liquids; per yr)			15,205,957	870,000	6,762,000	16,813,584		2,231,687	
Fuel replaced (GJ per year)			544,373	32,244	250,613	354,200		85,474	**1,266,904**
Useful by-product	fertilizer	fertilizer	fertilizer	glycerol	glycerol	vinasse		fertilizer	
Investment	258,000	1,920,000	27,930,000	510,375	3,570,161	18,175,000		6,234,000	**58,597,536**
Annualised investm. + O&M cost	157,996	1,413,869	15,023,052	577,970	10,462,766	12,815,762		634,947	**41,086,362**
Unit cost of energy	0.56 USD/kWh	0.22 USD/kWh	23.0 USD/GJ	17.92 USD/GJ	17.4 USD/GJ	36.2 USD/GJ		29.2	
Annual GHG avoidance (tCO2/yr)	224	5,107	29,941	2,436	18,934	38,517	20,016	5,898	**121,072**
Cumulative GHG	1,448	32,973	598,811	38,976	302,938	616,265	129,227	94,363	**1,814,999**

Box 22 Contribution of bioenergy to energy supply and demand in 2020 and 2040

Energy supply and demand, 2020 (see Box 1)



Projection of low-carbon energy supply to meet 2040 demand