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92

ENERGY

BIOENERGY AND FOOD SECURITY (BEFS) ASSESSMENT SEYCHELLES

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FOREWORD

With a growing population, economic growth, and urbanization, the demand for energy is increasing. Energy mainly comes from the burning of fossil fuels, which in turn contributes to global greenhouse gas emissions. Like most Small Islands Developing States, Seychelles imports around 95 percent of its energy needs, and as a country we aim to transform our energy sector into a low-carbon one. Thus, we need to recognize the role that Renewable Energy can play in this transformation. This critical role will not only address the energy challenges, but also contribute to the achievement of the Sustainable Development Goals and the Paris Agreement.

Bioenergy is considered as one of the forms of renewable energy that can contribute to this transformation along with solar and wind energy. But by how much? This report investigates the country's biomass potential and provides an initial look at the contribution that bioenergy can make to our energy sector. Clearly, for us to achieve a sustainable energy sector and strengthen our energy security we must look at all available renewable energy resources. Like all forms of renewable energy, bioenergy has many benefits and therefore its potential should be carefully assessed.

I would also like to point out that this report examines biomass sources, including in the agriculture sector, which fits in well with the current water-food-energy nexus conversation. Energy and agrifood systems are closely linked. In fact, more than one-quarter of the energy used globally is consumed within the agrifood system. By looking at bioenergy we are adding value to biomass sources, especially within agrifood systems. Furthermore, this aligns well with my ministry's priority to promote innovative and sustainable agrifood practices in the face of climate change.

To conclude, I would like to thank the authors and everyone who has contributed to preparing this interesting and insightful report. We have much to gain by sharing our knowledge, experiences and ideas with each other. Shaping the future for a clean and sustainable energy system is a collective effort, and we will need "all hands on deck."

Mr. Flavien Joubert,
Minister for Agriculture,
Climate Change and Environment of Seychelles for the BFES report.

ABBREVIATIONS AND ACRONYMS

AD	anaerobic digestion
BEFS	bioenergy and food security
CHP	cogeneration of heat and power
CBG	compressed biogas
CSTR	continuous stirred tank reactor
EEZ	exclusive economic zone
FAO	Food and Agriculture Organization of the United Nations
FRA	Global Forest Resources Assessment
GDP	gross domestic product
GHG	greenhouse gas
HRT	hydraulic retention time
IDC	Island Development Corporation
IOT	Indian Ocean Tuna Limited
LHV	lower heating value
LULUCF	land use, land use change and forestry
LWMA	Landscape and Waste Management Agency
MAI	Mean annual increment
MBT	mechanical biological treatment
MED	multiple effect distillation
MEECC	Ministry of Agriculture, Climate Change and Environment
MFD	multistage flash distillation
MoFA	Ministry of Fisheries and Agriculture

MPZM	market profitability zone maps
MSW	municipal solid waste
NDC	nationally determined contributions
NDS	National Development Strategy
NES	not elsewhere specified
PUC	Public Utilities Corporation
PV	photovoltaic
RCR	residue to crop ratio
RMP	realistic methane potential
SAA	Seychelles Agricultural Agency
SEC	Seychelles Energy Commission
SIDS	Small Island Developing Stated
SNPA	Seychelles National Parks Authority
SSDS	Seychelles Sustainable Development Strategy
STAR	Société de Traitement et d'Assainissement Régionale
SWRO	seawater reverse osmosis
TOE	tonnes of oil equivalent
TS	total solids
VS	volatile solids
WWTP	wastewater treatment plant

EXECUTIVE SUMMARY

A sustainable energy supply is essential for a country's stability and wellbeing. Seychelles, like many Small Island Developing States (SIDS), currently depends on imported energy, in the form of fossil fuels.

To limit this dependence, it is aiming to increase its reliance on renewable energy to 15 percent by 2030, with a long-term ambition of using 100 percent renewable sources. Despite favourable conditions for renewable energy resources, such as wind and solar, very little has been tapped so far. The high dependence on fossil fuel imports means Seychelles is highly vulnerable to disruptions in global markets. The situation is exacerbated by a reliance on imported food, which accounts for about 70 percent of food consumption. The vulnerability and the risk for Seychelles to global shocks cannot be underestimated.

Sustainable bioenergy is one form of renewable energy that can be used to green a country's energy mix. This Sustainable Bioenergy Assessment report for Seychelles assesses the potential for sustainable bioenergy within the country, a means to help protect the country from global shocks, and to provide alternative sources of energy. The report considers sustainable biomass sources from the agriculture, forestry and waste sectors.

Managed sustainably, bioenergy can provide multiple benefits in parallel to energy provision. These include jobs, agricultural and renewable energy investment and waste management. However, sustainable bioenergy development remains a complex topic due to the vast breadth of biomass options that can be sourced, the variety of technologies available, and the final economic and financial viability of the systems.

The assessment was conducted following the Bioenergy and Food Security (BEFS) Approach of Food and Agriculture Organization of the United Nations (FAO) (FAO, 2014b), and looked at different available bioenergy pathways. Within the report, the different forms of biomass, their availability and advantages, are assessed. Livestock, crop and forestry residues, and the biodegradable portion of waste, otherwise destined for landfill, are among the sources considered for the production of bioenergy. These biomass types are then assessed from a technical and economic viewpoint, under different market scenarios, for the production of energy. The most viable form of bioenergy production is presented, alongside estimates of the production costs, the investment requirements and the related greenhouse gas (GHG) savings. The assessment shows that electricity generation, through biogas conversion, is the most promising pathway under the Seychellois' context. The analysis also indicates that waste-to-energy technologies can be potentially profitable in Seychelles while reducing the amount of waste sent to landfills and turning biomass residues into valuable sources for electricity generation. This approach will also bring benefits in terms of GHG emission savings and reduction on the fossil fuel dependence for electricity generation on the island. As a first step in developing a waste to energy production pathway that uses the biodegradable portions of landfill waste, it would be necessary to establish a collection value chain for the waste to be used. The local waste management company could be a key partner in this. Once the value chain for biodegradable portion of municipal solid waste is established, it will be possible to also include the collection of livestock manure and biodegradable commercial waste, to reach the estimated electricity generation potential.

CHAPTER

1

INTRODUCTION

CHAPTER

2

BIOENERGY AND FOOD ASSESSMENT: COUNTRY CONTEXT

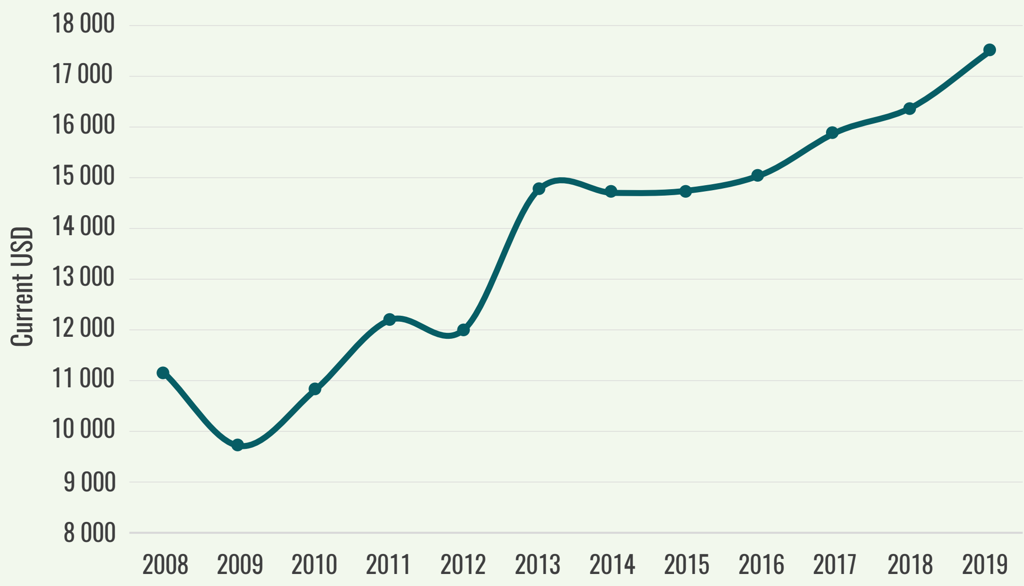
The Seychelles is an archipelago comprising 155 islands in the Indian Ocean, located about 1 500 km east of the mainland of Africa (Kenya) and northeast of Madagascar. Its land area covers 45 900 hectares and 41 of the islands are granitic with rugged topography. These islands include the so-called inner islands, of which Mahé (15 700 hectares), Praslin (3 800 hectares) and La Digue (1 000 hectares) are the most important ones. All granitic islands are situated within a radius of 50 km of Mahé. The remaining islands are coralline scattered throughout the archipelago and scarcely a few meters above sea level. The current population of the Seychelles is around 98 000 inhabitants, with the majority of the population living on the three main islands (World Bank, 2020). The country gained independence from the United Kingdom of Great Britain and Northern Ireland in 1976 and has since embarked on a series of economic reforms, particularly after the economic crisis of 2008.

2.1 ECONOMY

The Seychelles has observed high rates of gross domestic product (GDP) growth over the recent years and reached a high income country status in 2014 (World Bank Group, 2017). The GDP per capita (in current US dollars) has grown steadily over the past 10 years since the debt default and economic crisis in 2008-2009 (**Figure 1**).

FIGURE 1.

GDP PER CAPITA



Source: World Bank, 2020.

Following the economic crisis, the Seychelles made significant progress achieving economic stability and fiscal sustainability through a conservative reform programme. As a result, the economy grew at an average rate of 4.2 percent per annum between 2009 and 2019, however, the GDP growth rates have been very volatile (**Figure 2**). The government maintained its target of 2.5 percent primary balance and remained on target to reduce the debt to GDP ratio to 50 percent by 2021 (World Bank, 2020).

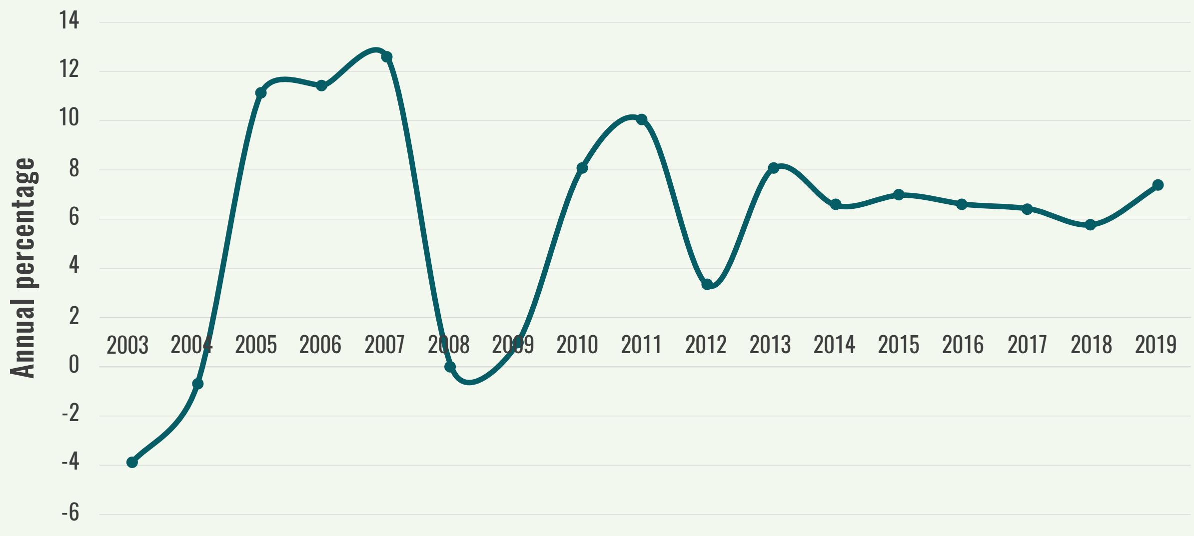
The fiscal balance declined to a slight deficit in 2019 (0.1 percent) due to increased capital outlays. The current account remained in deficit, hovering around 17 percent of the GDP and was substantially financed by foreign direct investment. The current debt is 58 percent of the GDP, which is down from 130 percent during the 2008 financial crisis (African Development Bank, 2020).

The economic and social shock from COVID-19 on the Seychellois economy was severe due to the country's strong dependence on international tourism. The GDP is expected to contract by 15.9 percent in 2020 as compared to the pre-pandemic projected growth rate of 3.5 percent (World Bank, 2020). The Seychellois economy is predominantly service oriented, with services contributing 83.4 percent to the country's economy in 2019. The secondary and primary sector contributed 13.9 percent and 2.6 percent to the GDP respectively (National Bureau of Statistics, 2020a) (**Figure 3**). The economy is heavily reliant on tourism, making it vulnerable to external shocks especially since the number of tourists visiting the country can be volatile and is susceptible to the economic conditions in their home countries. The tourism industry accounted for 24.4 percent of the total GDP in 2019 (National Bureau of Statistics, 2020a). In 2019, 69 percent of the tourists came from Europe, followed by Asia with 17 percent (National Bureau of Statistics, 2021).

The country is also dependent on the fisheries sector and sustainable use of ocean resources for economic growth, job creation and livelihood improvement within the framework of the Blue Economy. The fisheries sector accounts for about 7.7 percent of the total GDP in the Seychelles (Government of Seychelles, 2020). In the Seychelles context, the Blue Economy refers to those economic activities that directly or indirectly occur in the ocean and coastal areas and that use outputs from the ocean in addition to the contribution of these activities to economic growth, social, cultural and environmental wellbeing.

FIGURE 2.

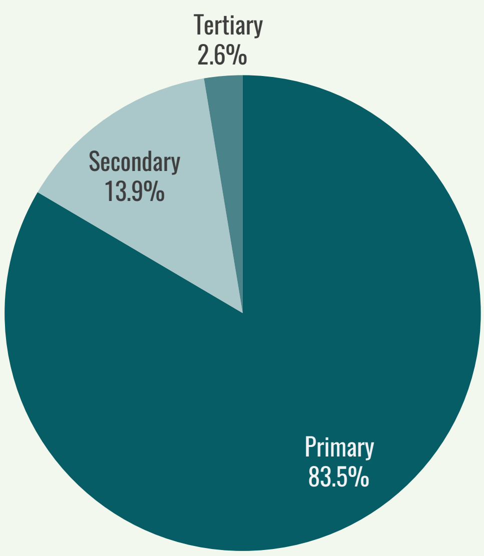
SEYCHELLES GDP GROWTH



Source: World Bank, 2020.

FIGURE 3.

GDP BY SECTORS



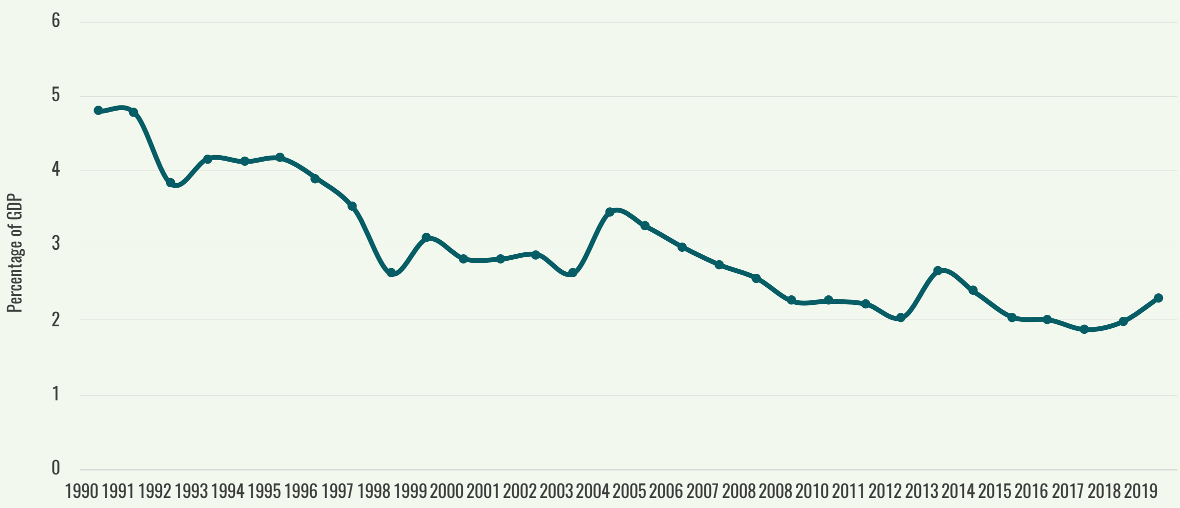
Source: National Bureau of Statistics, 2020a.

Given the limited arable land available in the country, the Seychelles has a relatively small agricultural sector, which has seen a downward trend in its contribution to the GDP during the past three decades (**Figure 4**). Of the total employed population in the country, only around

1.2 percent work in the agriculture sector, while around 76.0 percent of the working population is employed in the tertiary sector (National Bureau of Statistics, 2020b) (**Figure 5**).

FIGURE 4.

AGRICULTURE VALUE ADDED



Source: World Bank, 2020.

The African Development Bank (2018) identified climate change, in particular the rise in the sea level, as a major challenge for the Seychelles. Diversifying the economy in order to absorb external shocks, especially to the tourism sector, is a key strategy that needs to be pursued in the country. Since 2015, the economic activity has focused even further on the dominant service sector; however, such a concentration lowers the country's resilience. The World Bank Group (2017) also identified four main constraints that hinder the Seychelles from reaching its true economic potential: i) access to credit; ii) high energy costs; iii) logistics and connectivity costs; and iv) a private sector enabling environment. Many of these constraints stem from the geographic location of the country as well as the lack of natural resources.

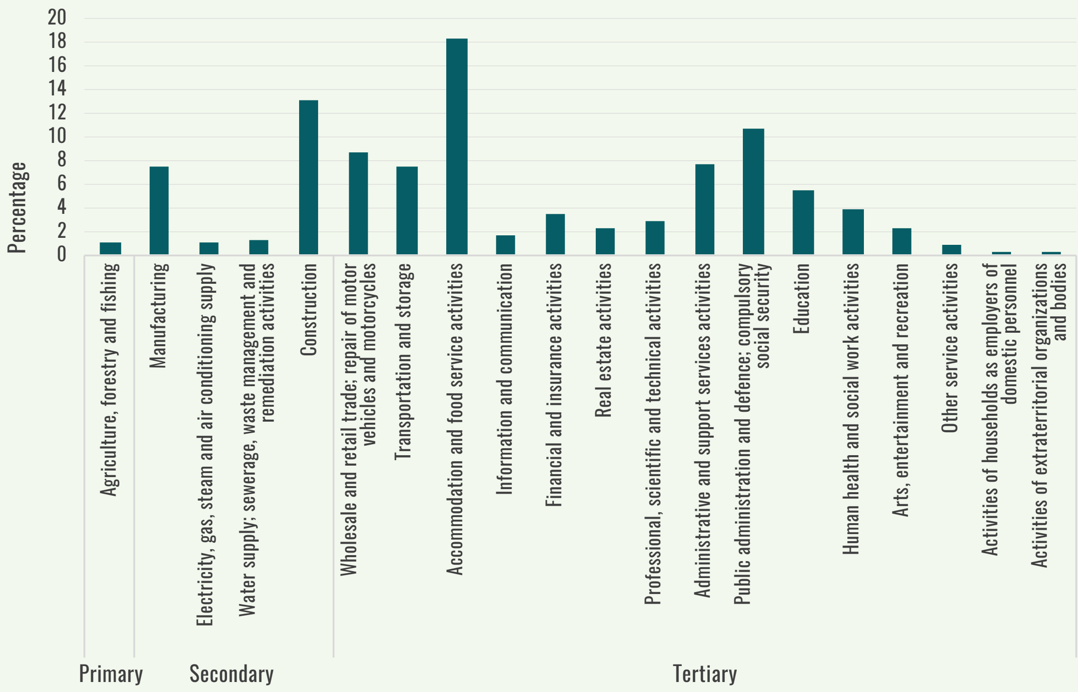
Although the country has the highest GDP per capita in Africa, inequality is significant, placing the prospect of continued shared prosperity in tighter focus (World Bank, 2020). The Seychelles had an overall low unemployment rate of 3.5 percent in 2018, however, youth unemployment was relatively high at a rate of 14.5 percent, primarily due to a mismatch between their skills level and the needs of businesses. This has led to the use of expatriate labour, even for unskilled jobs (African Development Bank, 2020).

In 2019, the Seychelles launched Vision 2033 (Ministry of Finance, Trade, Investment and Economic Planning, 2019a) and its accompanying National Development Strategy (NDS) 2019-2023 (Ministry of Finance, Trade, Investment and Economic Planning, 2019b). Vision 2033 provides a roadmap for the country's development until 2033 with the objective to transform the Seychelles into "a resilient, responsible and prosperous nation of healthy, educated and empowered Seychellois living together in harmony with nature and engaged with the wider world."

Vision 2033 and the NDS 2019-2023 are both designed around six thematic pillars. The environmental sustainability and resilience pillar seek to protect the natural environment, as well as human and ecological health, while driving innovation and enhancing quality of life. This includes increasing the country's energy and food security, as currently the Seychelles are almost entirely reliant on imported fossil fuels for electricity as well as on imported food.

FIGURE 5.

EMPLOYMENT BY SECTOR



Source: National Bureau of Statistics, 2020b.

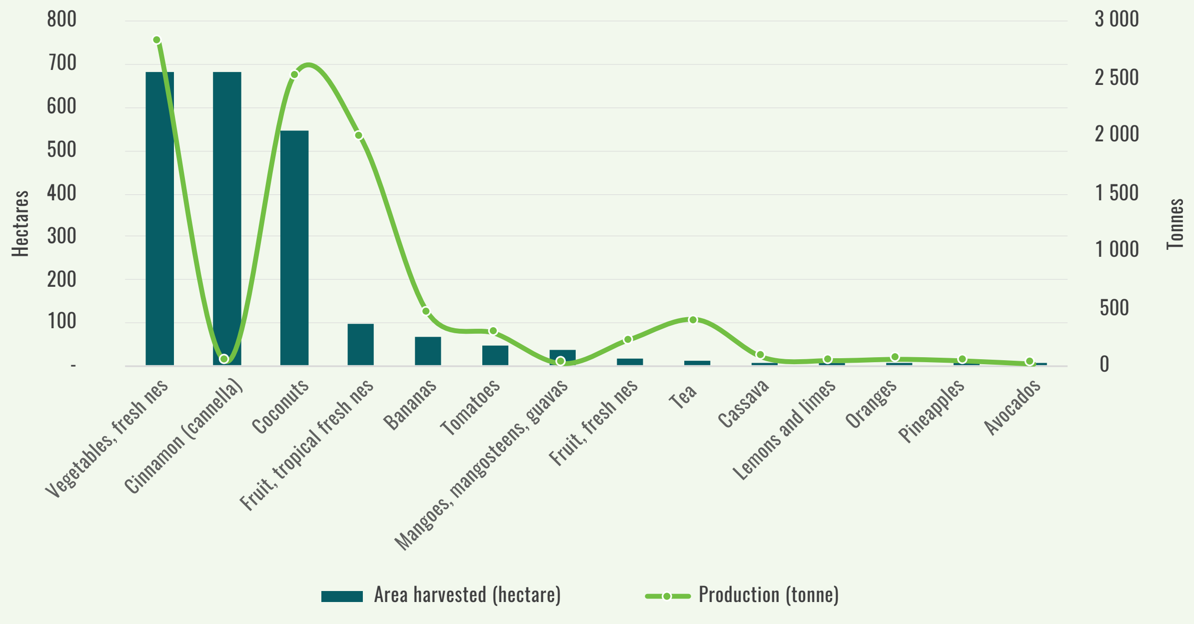
2.2 AGRICULTURE

Agriculture in the Seychelles is dominated by registered commercial farmers and household gardens, which are characterized by rainfed production with low productivity levels. Arable land is a scarce resource and, the country is known for having one of the lowest arable lands per person in the world (World Bank Group, 2017). The country has a narrow agricultural production base, with only 640 registered farmers, 1 330 artisanal fishers and an estimate of 5 000 backyard farmers (Seychelles Agricultural Agency, 2020).

Agricultural land is limited because of Seychelles' granitic surface and due to the fact that 50 percent of Mahé, Praslin and La Digue are protected forests. The development of mainly the tourism sector coupled with accelerated urbanisation, have resulted in important losses of agricultural land (IFAD, 2016). According to the Seychelles Agricultural Census, the total agricultural area in the Seychelles was 466 hectares in 2011, but only 95-100 hectares were under intensive production (Government of Republic of Seychelles, 2011). The main crops produced in the country by volume are vegetables, coconuts and bananas (**Figure 6**). The livestock sector is dominated by some large producers, particularly pig farmers and poultry farmers (both layer and broiler farms). Because of the limited amount of land available, cattle are farmed to a very limited extent only. Livestock production has been declining since 2006 (**Figure 7**) due to trade liberalization and more economical imports of meats and meat products (Ministry of Fisheries and Agriculture, 2015). As regards fisheries, the country is located in one of the most productive fishing grounds in the South-West Indian Ocean and has a vast exclusive economic zone (EEZ) of 1 374 million km^2. The sector spans all scales of production from industrial large-pelagic fishery, to small-scale artisanal fishery. Fisheries play an important role in the nutrition of the population with per

FIGURE 6.

CROPS PRODUCED IN SEYCHELLES (PRODUCTION AND HARVESTED AREA – AVERAGE 2014-2018)



Source: FAOSTAT, 2020.

capita fish consumption of around 65 kg/p.a. The majority of fish for local consumption is supplied by artisanal fishing (IFAD, 2016).

In 2017 the catch of the local fisheries sector amounted to 4 211 tonnes (**Figure 8**). It is comprised of two distinct sub-sectors:

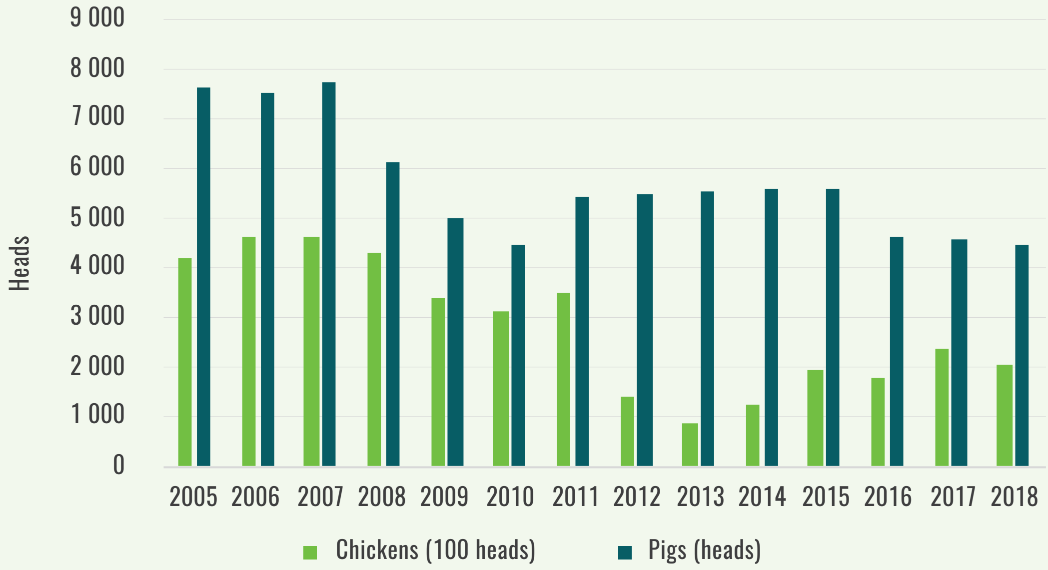
- the artisanal sub-sector, which is exclusively reserved and practised by Seychellois fishermen and targets demersal and pelagic species, and;
- the semi-industrial sub-sector, which is comprised of locally-owned longline vessels targeting tuna and tuna-like species as well as vessels licensed for harvesting sea cucumber (Ministry of Fishery and Agriculture, 2019).

Industrial fishing in the Seychelles is dominated by tuna, which is conducted by both Seychelles flagged tuna vessels and foreign tuna fleets. A total of 80 percent of the total catch (341 870 tonnes) in the Western Indian Ocean is transacted through Port Victoria for transhipment and landing (20 percent) at Indian Ocean Tuna Limited (IOT) (Ministry of Fishery and Agriculture, 2019).The agro-processing sector is limited due to the lack of arable land in the country. The major agro-processing industries are beer, fish and coconuts (for oil). Canned tuna is the major product, with an output of around 45 800 tonnes in 2019. Beverage production is another major agro-processing sector dominated by beer production. The country produced around 6 032 000 litres of beer and stout in 2019 (National Bureau of Statistics, 2020c). Given the small agriculture sector, the Seychelles is a net importer of most foods, in fact, it has been importing close to 75 percent of its food requirements. The 2008 global food crisis revealed the Seychelles' vulnerability to food security (IFAD, 2016). Most of the country's exports include canned tuna, fish, fish products, cinnamon and beverages (FAO, 2020; National Bureau of Statistics, 2020d).

A growing population (albeit gradual) and international factors such as change and uncertainty in the global food systems, and

FIGURE 7.

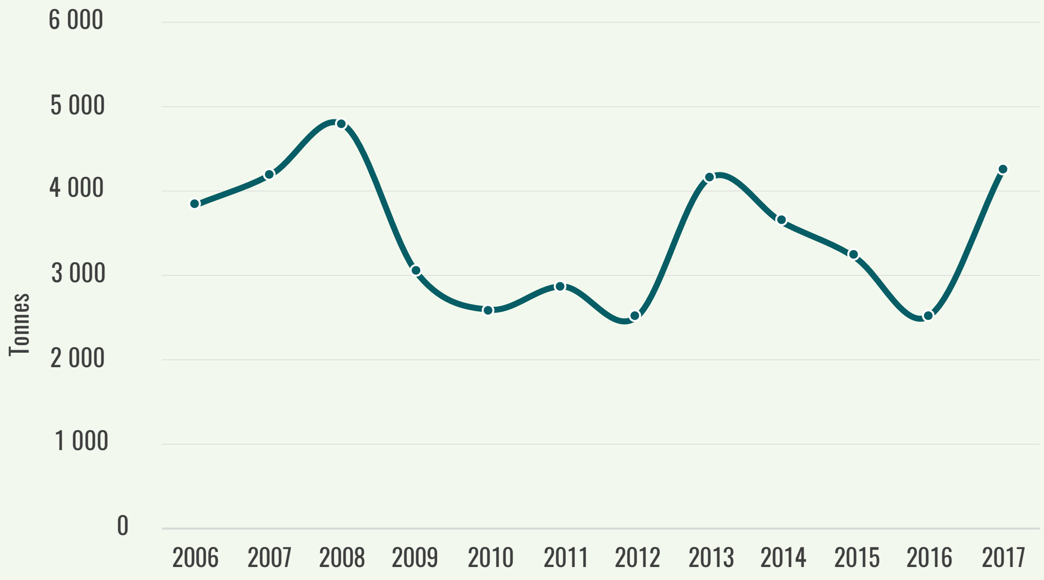
LIVESTOCK PRODUCTION IN THE SEYCHELLES



Source: FAOSTAT, 2020.

FIGURE 8.

ARTISANAL FISHERIES CATCH



Source: Ministry of Fishery and Agriculture, 2019.

the volatility of food prices caused by climate change, for example, impact heavily on food and nutritional security (Government of Republic of Seychelles, 2013). This confirms the importance of domestic food production, as a result, the issue of national nutrition and food security has been given the highest priority in the Seychelles (Ministry of Fisheries and Agriculture, 2015).

In early 2013, the Government of the Seychelles developed a comprehensive food and nutrition security policy document: the National Food and Nutrition Security Policy. It was developed to align and strengthen the country's capacity and ability to deliver on its food and nutrition security objectives, ensuring efficiency and sustainability in the use of resources, effective institutions, and resilience in the face of internal and external shocks. It also provided the basic policy framework for the implementation of the Seychelles National Agricultural Investment Plan (Ministry of Fisheries and Agriculture, 2015), which seeks to harmonize, consolidate and accelerate the implementation of the country's agriculture and food security, as well as nutrition-related policies and strategies during the period 2015 to 2020.

As far as the agricultural sector is concerned, Vision 2033 strives for a resilient, innovative, high-value and climate-smart agricultural sector that will contribute to food security for the Seychelles, and furthermore lead to an increase in labour as well as improve the quality of labour in this sector.

2.3 FORESTRY

The Seychelles forestry sector is generally perceived as marginal. The sectoral GDP contribution, including the wood industries, does not exceed 0.1 percent (FAO, 2008). Although forests are not a major source of timber, they play a vital role in the country's economy in that they provide different ecosystem services, for example, the amenity value that is important for tourism as well as erosion and watershed protection.

Forests cover 90 percent of the total land area of the country (40 600 ha) with a total growing stock estimated at 3.1 million m^3. State forests cover 77 percent and private forests 23 percent of the forest area. About 50 percent of the forests are located within national parks or other conservation areas (FAO, 2014).

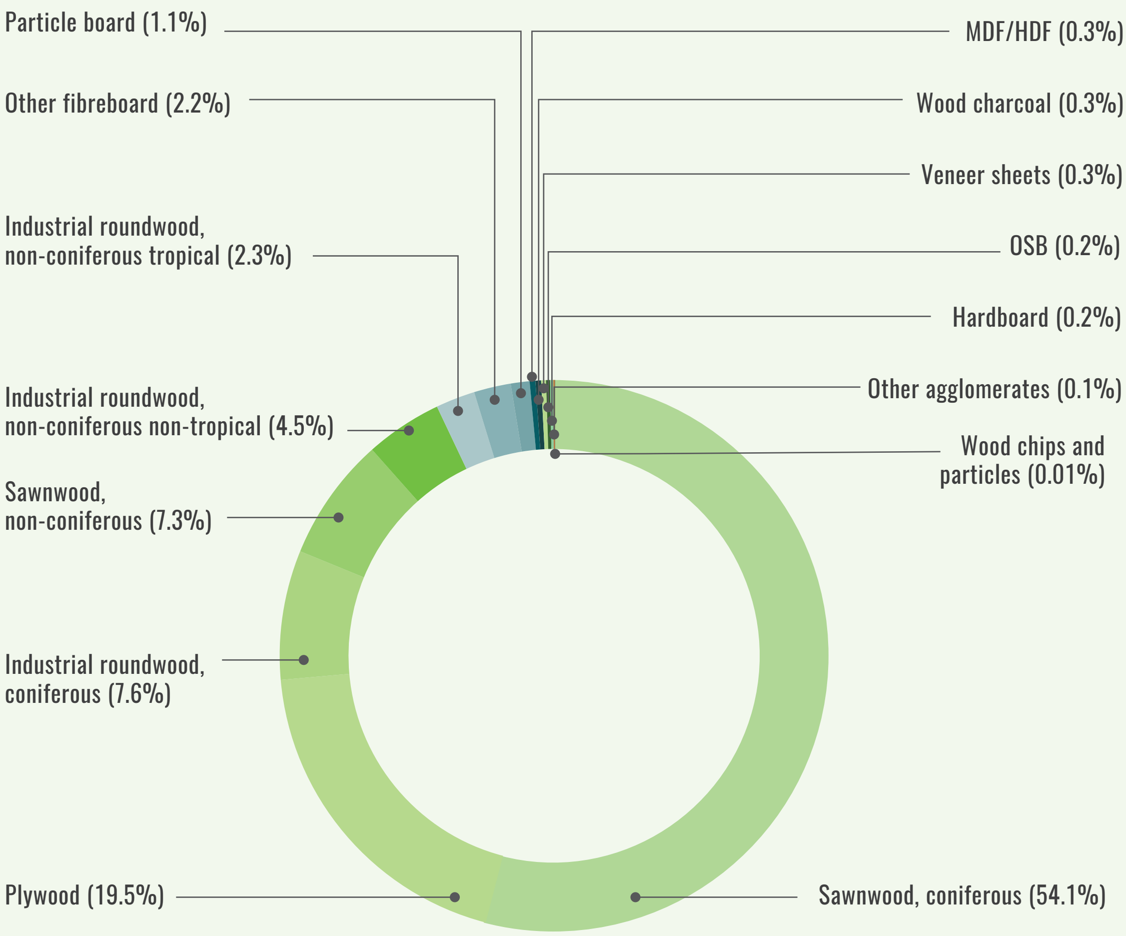
As a result of human activities, the forests have seriously deteriorated and have a high share of non-native species. Forest Resource Assessment (FRA) (FAO, 2014):

- Primary forests no longer exist, except as relict vegetation at the highest altitudes and on glacis.
- 63 percent of the forests are secondary forests, and most of them have been invaded by non-native species.
- Invaded bush vegetation covers 17 percent of the total forested land, mainly on the granitic islands.
- Plantations occupy 12 percent of the forests, however, only 10 percent of these plantations are on granitic islands (mainly of *Swietenia macrophylla).* The rest is managed *Casuarina equisetifolia* forests on the outer islands.
- Coconut plantations occupy 7 percent of the forests.

Total wood removals in the Seychelles amount to 12 800 m^3 per year (u.b.) (FAO, 2014). On the other hand, the quantities of wood products imported are larger and the total import amounted to 24 000 m^3 in 2019. The main products imported were sawnwood (61.3 percent) and plywood (19.5 percent) (**Figure 9**).

FIGURE 9.

IMPORT OF WOOD PRODUCTS



Source: FAOSTAT, 2020.

The main forest management problems in the Seychelles include housing encroachment due to land pressure, invasive exotic plant species competing with endemic and indigenous species for the habitat, and the prevention and control of forest fires, which have had disastrous effects on soil and water conservation. The main problems encountered with utilising wood feedstock are the difficult access to the forests, low productivity of both harvesting and processing, and consequently high extraction costs (Ministry of Natural Resources and Tourism, 2001). Destruction of forests in the Seychelles is prohibited by the Breadfruit and Other Trees (Protection) Act.

The Seychelles Sustainable Development Strategy 2012-2020 (SSDS) (Government of Republic of Seychelles, 2011) stipulates three main goals concerning the forestry sector:

- conserve and manage terrestrial and aquatic biodiversity to ensure sustainable use and equitable benefits for the people;
- improve the understanding of biological diversity and ecosystem functioning in a changing environment;
- achieve sustainable forest management using an ecosystem approach, which further strengthens ecosystem services.

2.4 WASTE MANAGEMENT

Waste management poses a significant challenge to the Seychelles when dealing with issues usually associated with managing waste

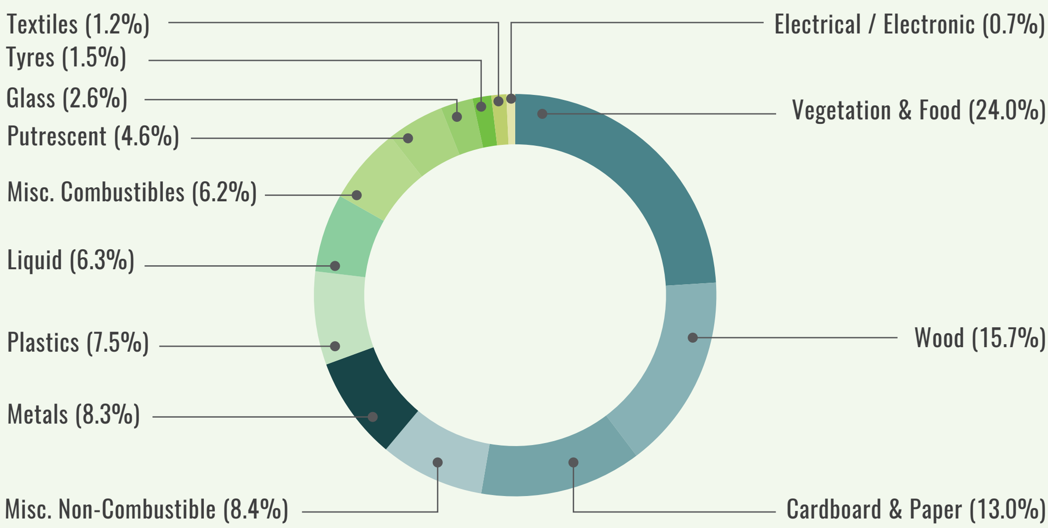
within a small island developing state, such as the lack of funding and capacity, high costs of transportation, absence of engineered landfills and limited land area available for storage of waste.

Currently, all major fractions of waste with the exception of polyethylene terephthalate (PET), aluminium cans, and large scrap metal are landfilled. Other waste fractions with a high recycling potential, notably glass, paper, and organic waste, have high landfilling rates. Organic waste has the highest contribution to landfill composition, which could be substantially reduced by anaerobic digestion (AD) or composting. Moreover, landfilling poses significant environmental problems and because land is scarce and expensive in the Seychelles, it will incur high costs to the government in the future (Meylan ***et al.***, 2018).

Seychellois waste generation has been increasing due to economic development and tourism, and consumption is expected to continue to rise in the near future, while landfill construction has not kept up with waste generation. Currently, around 70 000 tonnes of waste are being delivered to the Providence landfill in Mahé annually. An additional 10 500 and 1 100 tonnes are delivered to the landfills on Praslin and La Digue, respectively.

FIGURE 10.

PROPORTION OF DIFFERENT WASTE STREAMS OF THE TOTAL WASTE IN MAHÉ



Source: Lai ***et al.****, 2016.*

Proportions of different waste streams of the total waste in Mahé is shown in **Figure 10**. Biodegradable waste (cardboard and paper, wood, vegetation and food and putrescent waste) creates 57.3 percent of the total waste. Metal and plastic waste also contribute significantly to total waste quantities by 8.3 and 7.5 percent, respectively. The Landscape and

Waste Management Agency operating under the Ministry of Agriculture, Climate Change and Environment (MAECC) is in charge of organising cleaning of public spaces and waste collection. The ministry is responsible for the development and implementation of all waste management policy, legal and regulatory frameworks.

The SSDS 2012-2020 set an overarching policy framework for sustainable development in the Seychelles. It contains a thematic policy on water, sanitation and waste management, with one of the three goals being the integrated and environmentally safe management of solid waste. The recently published NDS 2019-2023, contributing to Vision 2033, states that waste-to-energy conversion could potentially be considered for the Seychelles, as this could feasibly represent a sustainable pathway to reducing greengouse gas (GHG) emissions, cleaning up waste from the environment and curbing the expansion of landfills.

The Government of the Seychelles has recently strengthened its commitment to improving the existing waste management system by adopting a new National Waste Policy 2018-2023. The overall goal is to ensure that "waste is managed in a sustainable manner, following the set guiding principles and approaches, in order to protect the integrity of the environment and improve the quality of life in the Seychelles". It outlines the priority objectives and provides direction on how these objectives should be met. Moreover, the ministry is currently developing the Seychelles Waste Master Plan (COWI, 2019) for a sustainable waste management system in the Seychelles.

2.5 ENERGY

The Seychelles, like many small island developing states have limited fossil fuel resources, hence, it depends heavily on imported fossil fuels to meet its energy needs. This results in high energy supply costs due to limited economies of scale effects, as well complicated and resource-intense transport (Wehner at al, 2020).

The Seychelles imports petroleum fuel to meet most of its primary energy needs to supply international aviation and international marine bunkers. Around 58 percent of fuel imports is used to supply international marine bunkers and international aviation while 42 percent is used to supply domestic consumers. Gasoil, fuel oil and Jet A account for 92 percent of the country' fuel import, the rest is composed of gasoline, LPG and avgas. **Table 1** provides information on the energy balance for the Seychelles for 2019.

TABLE 1.

NATIONAL ENERGY BALANCE FOR 2019

	PETROLEUM PRODUCTS					
Unit: TOE (Tonne of Oil Equivalent)	Gasoline	Gasoil	Fuel Oil	Jet A1	LPG	Kerosene
PRIMARY ENERGY PRODUCTION & ENERGY SUPPLIES						
Primary Energy Production						
Imports	25 784.63	230 908.6	91 826.68	53 679.20	7 360.07	
Exports (-)	-	-	-	-	-	-
International Marine & Air Bunkers (-)		(180 774.9)	(6 876.0)	(50 456.8)		
Stock Change (+ taking from stock. - feeding into stock)	537.8	12 463.5	(1.206.6)	953.4	(1 854.9)	17.4
Loss (-) or Gain (+)	812.9	(3 560.3)	(1.360.8)	224.2	(312.4)	0.7
Inter Product Transfer	1.1					
TOTAL PRIMARY CONSUMPTION (1)	**27 136.5**	**59 036.8**	**82 383.3**	**4 400.0**	**5 192.8**	**18.1**
Energy Independence Rate						
SECONDARY PRODUCTION						
Electricity Generation from HFO and LFO by PUC		(13 197)	(85 997)			
Electricity Generation from LFO by Auto-producers		(20 099.6)				
Electricity Generation from grid-connected Solar PV						
Electricity Generation from Wind by PUC						
Electricity Generation from off-grid Solar PV						
Production of Solar Heat / Solar Water Heaters						
TOTAL SECONDARY PRODUCTION (2)	**-**	**(33 296.6)**	**(85 997.3)**	**-**	**-**	**-**
ENERGY SECTOR OWN CONSUMPTION						
Electricity consumption for power stations						
Heat consumption for Fuel Oil Treatment						
DISTRIBUTION OF ENERGY						
Losses in transportation and distribution						
TOTAL FINAL DISTRIBUTION (1+2+Losses)	**27 136.5**	**25 740.2**	**(3 614.0)**	**4 400.0**	**5 192.8**	**18.1**
FINAL ENERGY CONSUMPTION						
Residential					3 915.9	3.8
Service	288.8	1 248.5			1 545.3	23.7
Industry	34.6	3 749.1	3 917.6		305.6	4.5
Road Transportation	23 981	12 979.6				
Domestic Air Transportation				3 680.3		
Maritime Transportation	925.0	3 884.8				
Artisanal Fishing		2 157.0				
TOTAL FINAL ENERGY CONSUMPTION	**25 229.1**	**24 019.1**	**3 917.6**	**3 680.3**	**5 766.8**	**32.1**

Source: Seychelles Energy Commission, 2019.

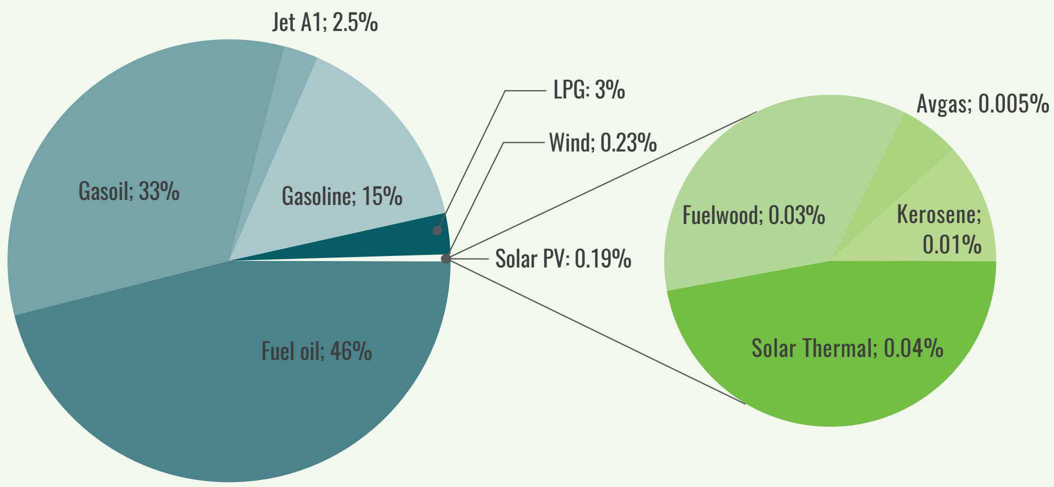
In 2019, the country's primary energy consumption was 179 062 toe and its per capita primary energy consumption 1.83 toe, which is close to the world's average. The primary

	BIOMASS	SOLAR		WIND	ELECTRICITY		HEAT		TOTAL
Avgas	Fuelwood & charcoal	Solar PV	Solar Thermal	Wind	Prod. (+)	Cons. (-)	Prod. (+)	Cons. (-)	
	58.05	435.5	74.4	319.0					886.9
12.33									409 571.5
-									-
									(238 107.7)
(4.28)									10 906.3
0.02									(4 195.8)
									1.1
8.1	**58.1**	**435.5**	**74.4**	**319.0**		**-**		**-**	**179 062.4**
									0.50%
						37 701.4			(61 492.9)
						6 974.6			(13 125.0)
		(341.7)				341.7			-
				(319.0)		319.0			-
		(93.8)				93.8			-
			(74.4)					74.4	-
-	**-**	**(435.5)**	**(74.4)**	**(319.0)**		**45 430.4**		**74.4**	**(74 617.9)**
						(1 109.8)			(1 109.8)
									-
		-	-	-		(2 774.54)			(2 774.5)
8.07	**58.05**					**42 655.87**		**74.37**	**101 669.9**
	58.05					11 570.3		74.37	15 622.5
						24 295.2			27 401.6
						5 536.4			13 547.9
						-			36 960.4
7.8						-			3 688.1
						-			4 809.8
									2 157.0
7.8	**58.1**	**-**	**-**	**-**		**41 401.9**			**104 187.2**

energy of the Seychelles is composed mainly of petroleum fuels (99.6 percent) and marginally renewable energy (0.4 percent) (**Figure 11**).

FIGURE 11.

STRUCTURE OF PRIMARY ENERGY CONSUMPTION IN 2019



Source: Seychelles Energy Commission, 2019.

In 2019, the country's final energy consumption was 104 187 toe, of which 40 percent accounted for electricity and 60 percent for petroleum fuel (**Figure 12**). Consumption by the transport sector (air, road and sea) accounts for 44 percent of the final energy consumed, followed by the service sector at 26 percent, the residential sector at 15 percent, and the industrial sector at 13 percent (**Figure 13**).

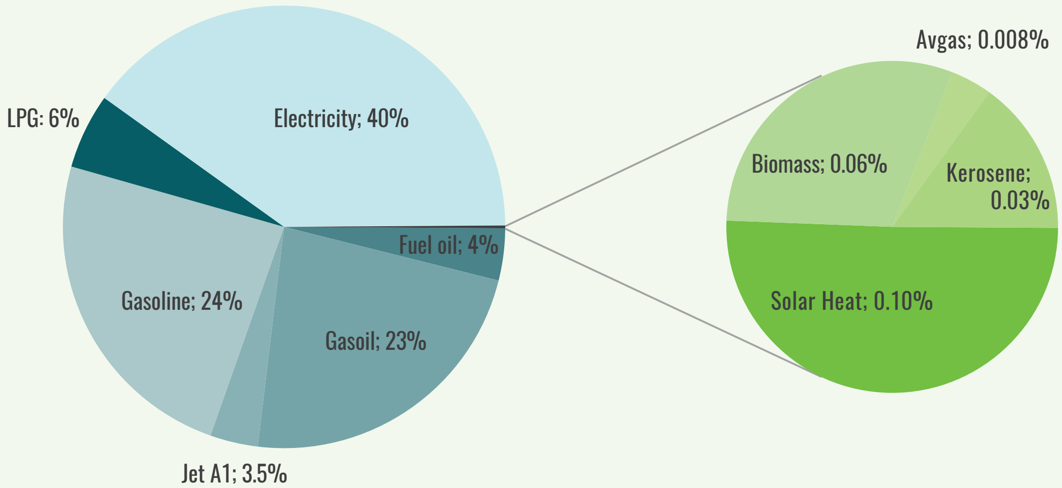
The fuels used in the transport sector include gasoil and gasoline for road transports, gasoil for sea transports, and Jet-A1 for air transports. Currently, there are a few electric and hybrid vehicles in the country, and almost every large hotel has a certain number of electric buggies that it uses on the premises and surrounding area. In 2019, the road transport sector consumed 36 960 toe of energy, of which roughly 65 percent for gasoline and 35 percent for gasoil. Gasoil is mainly used by large- and medium-size trucks, buses and some private and commercial vehicles, while gasoline is used by all other vehicles.

Cooking by most of the households, hotels, restaurants, fast food businesses, and other various users in industries, businesses and hospitals is carried out predominantly using LPG (Seychelles Energy Commission, 2017).

The entire population has access to electricity in the Seychelles (**Figure 14**). The Public Utilities Corporation (PUC) is a government-owned organization, which is responsible for the generation, transmission and distribution of electricity in the Seychelles. PUC has two thermal power stations on Mahé, namely Victoria C with an installed capacity of 74 MW, and Victoria B with a capacity of 16.7 MW. Additionally, PUC has a thermal power station on Praslin, with an installed capacity of 13.3 MW. Electricity is mostly produced using fuel oil (86 percent) and to a smaller capacity gasoil (14 percent).

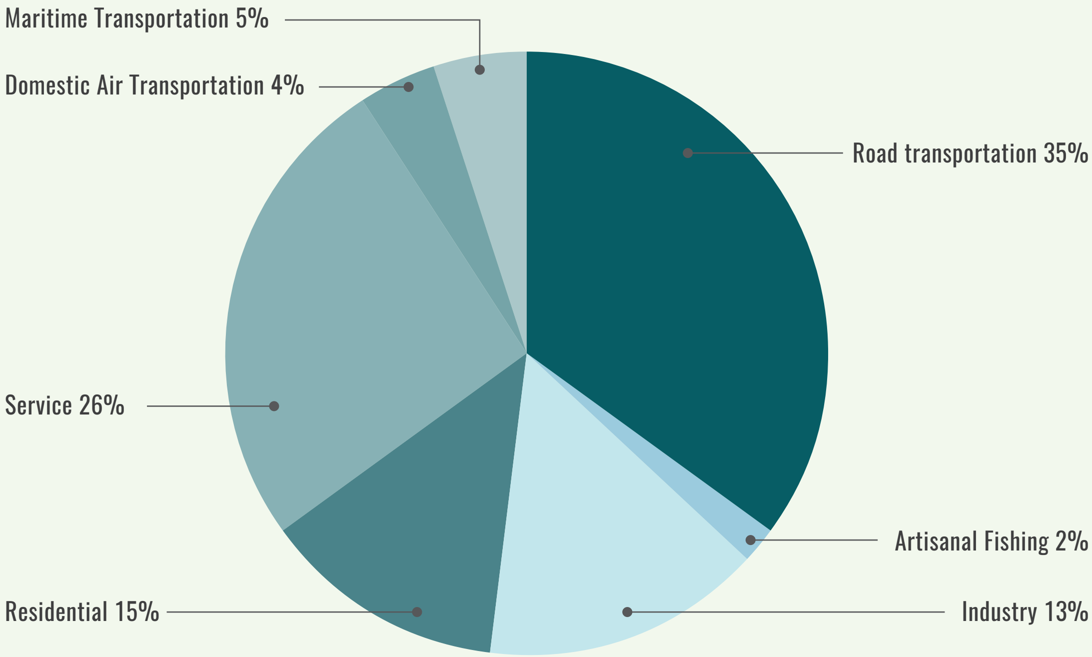
FIGURE 12.

FINAL ENERGY CONSUMPTION BY SECTOR FOR 2019



Source: Seychelles Energy Commission, 2019.

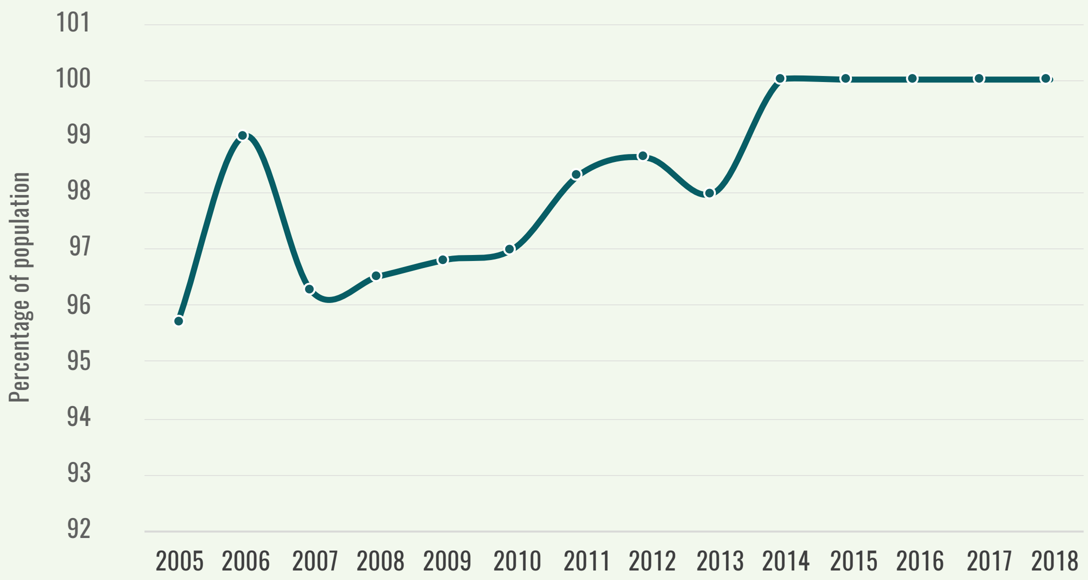
FIGURE 13.



Source: Seychelles Energy Commission, 2019.

FIGURE 14.

ACCESS TO ELECTRICITY



Source: World Bank, 2020.

Since 2013, PUC has also been operating a wind farm with a total capacity of 6 MW. There are also a growing number of grid-connected solar photovoltaic (PV) panels, which do not belong to PUC but generate electricity and feed into the grid. Their total installed PV capacity was 1.63 MW in 2016.

The distribution systems in the Seychelles are based on two main grids: the Mahé grid and the Praslin and La Digue grid. The Mahé grid is on the main island of Mahé and feeds some of the inner islands (Sainte Anne, Cerf Island) by way of sub-marine cables. The island of Praslin supplies electricity to the island of La Digue by way of sub-marine cables.

On the outer islands, the Island Development Corporation (IDC) is the authority responsible for the development of these islands, including electricity generation and supply. It uses diesel generators with a total generating capacity of roughly 10 MW, of which 83 percent is consumed on four islands namely: Desroches, Alphonse, Silhouette and Providence.

In 2015, PUC's total electricity generation was 377.6 GWh. All renewable energy plants produced a total of 8.34 GWh of electrical energy during 2015, representing 2.2 percent of total national electricity generated. The total electricity consumption was 324.2 GWh in 2015, with commerce and industry being the largest sector with a share of 57 percent, followed by the residential sector with a share of 29 percent. The total electricity consumption increased to 365.9 GWh in 2016.

Additionally, there are numerous auto-producers of electricity that generate electricity for their own consumption. Most of the auto-producers are large hotels on Mahé and Praslin, which are not connected to the grid due to its insufficient capacity. In 2015, auto-producers generated an estimated 62 GWh of electricity (Seychelles Energy Commission, 2017).

The Department of Energy and Climate Change within the MEECC oversees the energy sector in the Seychelles. The energy regulator is the Seychelles Energy Commission (SEC), while the PUC is the sole generator, transmitter and distributor of electric energy.

The SSDS 2012-2020 incorporates national priorities for sustainable development and formulates guiding principles for the energy and transport sector. According to the strategy, the "reliance on fossil fuels should be gradually reduced as they are not sustainable sources" and the "energy independence should be increased to reduce economic vulnerability through the

use of local sources of energy" (Government of Republic of Seychelles, 2011).

The main sector policy is the Seychelles Energy Policy 2010-2030 (Government of Seychelles, 2010). The policy recommends increased energy efficiency and an increasing contribution from renewable energy in the energy matrix. The targets for renewable energy contribution were 5 percent in 2020 and 15 percent in 2030, with the intention to diversify the energy base so that the total energy supply will be 100 percent, based on renewable energy in the long term.

The remoteness, the high dependence on fossil fuels, and the high expenditures for fuel imports underscore the economic relevance of a transition towards renewable energy deployment. While the potential for using renewable energies in the Seychelles is significant, particularly for solar and wind energy, those resources have been utilized only to a limited extent so far. The increased deployment of renewable energy would benefit the state for climate change mitigation, a decrease in the trade balance deficit, less exposure to volatile fuel prices, a more self-reliant electricity supply, lower imports of fossil fuels, and lower associated environmental risks (Wehner *et al.*, 2020).

In 2016 the idea of '100 percent Renewable Seychelles' gained momentum when a proposal to develop a 100 percent renewable energy roadmap for the Seychelles presented by the MEECC was adopted and approved by the Cabinet of Ministers (Government of Seychelles, 2016).

2.6 CLIMATE POLICY

Like most small island developing states, the Seychelles are facing extreme vulnerability to the adverse impacts of climate change. The major climate threats are extreme weather events and the rise in sea level, although other impacts such as changing precipitation, more frequent droughts, heat waves, coastal erosion, storm surges, tropical cyclones, ocean acidification and coral bleaching will become more common (Government of Seychelles, 2020).

The Seychelles has currently put into place the National Climate Change Policy (Government of Seychelles, 2020), which recognises the threats of climate change within different sectors. Given that over 90 percent of the critical infrastructures are located along the shoreline in the Seychelles, an increase in the average global temperature of 2°C would be catastrophic. Moreover, marine ecosystems will be greatly impacted by this projected rise in temperatures that will compromise the Blue Economy Strategy.

According to nationally determined contributions (NDC) (Government of Seychelles, 2015), the Seychelles main vulnerabilities with respect to climate change are in:

- critical infrastructure (roads, ports, electricity, water and sewerage management systems);
- tourism (areas in proximity to the coast or in areas vulnerable to flooding and landslides);
- food security (currently reliant on food imports);
- coastal and marine resources (considering the aims of the Blue Economy and Vision 2033);
- water security (particularly considering issues of storage and distribution);
- energy security (particularly considering the reliance on fossil fuels);
- health (particularly addressing the burden placed on high-density populations in the coastal areas and general vulnerability to climate-sensitive diseases);
- waste (particularly for landfill sites in high risk, coastal locations); and
- disaster preparedness (particularly addressing the need for more research to understand climate change impacts, and resources to predict, prevent and respond to disasters).

The total CO_2 emissions in the Seychelles, estimated in the Second National Communication (Ministry of Home Affairs, Environment, Transport and Energy, 2011) amounted to 273 148 t/year, while the total CO_2 removal capacity by the land use, land use change and forestry (LULUCF) sector was 837 380 t/year. This means that the Seychelles was a net sink of CO_2, at the level of 564 232 t/year.

Given that the Seychelles contributed approximately 0.003 percent of the world´s GHG emissions in 2011, it contributes only marginally to the global emissions on an absolute scale. However, an average of 5.38 tonnes/year of CO_2 is released per person, and this is growing annually. In particular, the energy sector is very carbon intensive – about 95 percent of GHG emissions come from the energy sector (mainly CO_2 emissions from electricity generation and transport). The remaining 5 percent is mainly methane coming from the wetlands and the landfills and emissions from industrial processes and agriculture are insignificant in the Seychelles (Government of Seychelles, 2015). Concerning forestry, it was estimated that 8 000 m^3 of biomass was harvested annually amounting to an annual emission of 12 542 tCO_2. The sink capacity of forests was estimated at 837 380 tCO_2 with an expected loss in sink capacity of 1 percent every five years (Ministry of Home Affairs, Environment, Transport and Energy, 2011).

The Seychelles plan to reduce its economy-wide absolute GHG emissions by 122.5 $ktCO_2e$ (21.4 percent) in 2025 and an estimated 188 $ktCO_2e$ in 2030 (29.0 percent) relative to baseline emissions (Government of Seychelles, 2015). Nevertheless, mitigation strategies have to be combined with adaptation strategies and measures, which are specific to impacts and the sector affected, so as to enable the Seychelles to cope with the negative impacts of climate change.

CHAPTER

3

BIOENERGY AND FOOD SECURITY (BEFS) ASSESSMENT: NATURAL RESOURCES

The aim of the assessment of natural resources is to determine the types of biomass that can serve as bioenergy feedstock, and to estimate their potential availability for energy generation. To ensure that bioenergy production is sustainable, the biomass currently used for other purposes is not deemed potentially available for bioenergy production. BEFS methodology also takes into account the sustainability of agricultural and forest ecosystems.

In line with the scope of the BEFS analysis for the Seychelles, the natural resources assessment was applied to two bioenergy feedstock groups:

- agriculture residues and biodegradable waste that can serve as feedstock for biogas production:
  - crop residues
  - livestock residues – manure
  - biodegradable waste.
- forest feedstock that can be used to produce electricity and heat:
  - harvesting residues from plantations
  - additional forest harvesting.

The BEFS assessment was implemented through a participatory process that included bilateral and multi-disciplinary technical consultations. In the following sections the BEFS assessment for each bioenergy feedstock type will be described.

3.1 AGRICULTURE

The agricultural sector in the Seychelles is managed by the Ministry of Fisheries and Agriculture (MoFA). The Ministry has the mission to:

- expand the domestic food supply base to improve the local contribution to the country's food security status;
- create a food basket with a higher nutritional value;
- enable the Seychelles to optimise on the use of its natural resources, providing opportunities to create jobs across the agriculture and food value chain.

The Seychelles Agricultural Agency (SAA) was established in 2009. The core mandate of the SAA is the execution of the National Food and Nutrition Security Policy (Government of Republic of Seychelles, 2013) and Seychelles National Agricultural Investment Plan (Ministry of Fisheries and Agriculture, 2015) under the supervision of the MoFA. The SAA supports the enhancement of national food security, facilitates the increase of contributions from agriculture to the country's GDP and facilitates the development and modernization of the agricultural sector.

The agricultural sector in the Seychelles has lost most of its economic importance over the past two decades. While at one time it was the mainstay of the Seychellois economy, nowadays agriculture contributes around 1.5 percent of the GDP. The performance of the sector oscillated at an average figure of SCR 214 million during the period 2012-2016 (Seychelles Agricultural Agency, 2020).

The agricultural sector of the Seychelles had to face many challenges during the trade liberalization in the late 2000s/early 2010s. The major challenges faced by the agricultural sector today are:

- low value addition to agricultural produce and limited market access;
- high level of post-harvest losses;
- limited arable land resource;
- low production and productivity dependent on season;
- weak implementation of agricultural laws and policies.

Agricultural land is scarce in the Seychelles because of its granitic surface and given that 50 percent of Mahé, Praslin and La Digue are covered by protected forests. The development of mainly the tourism sector coupled with accelerated urbanisation have resulted in important losses of agricultural land. Due to unsuitable policy measures, more than 80 percent of state agricultural land of the 1960s and 1970s has been diverted to other sectors. It is estimated that about 6 000 hectares are available for agricultural development, however most arable land is located in remote mountainous areas, which limits access to market and water supply (IFAD, 2016). According to the Seychelles Agricultural Census, the total agricultural area in the Seychelles was 466 hectares in 2011, but only 95-100 hectares were under intensive production (Government of Republic of Seychelles, 2011).

The agricultural sector is currently highly fragmented with 640 registered farmers and an estimate of 5 000 backyard farmers, accounting for an estimate of 15 percent of the market share. The average farm size is 0.8 hectares and rarely exceeds 2 hectares. The land utilization index is estimated to be in the region of 60 percent (Seychelles Agricultural Agency, 2020).

Livestock farming is predominantly oriented towards pig and poultry farming. Because of the limited land available, cattle are farmed to a very limited extent only. While the majority of registered farms are based in Mahé, only a few farms are based in other islands. Due to trade liberalization and more economical imports livestock farming has seen a decline during the last decade.

3.2 FORESTRY

MEECC principally safeguards the environment of the Seychelles. It is responsible for developing appropriate plans and policies for the sustainable conservation of biological diversity and supports local non-governmental organisations and private agencies engaged in environmental matters; furthermore, it regulates activities impacting the environment and natural resources.

The Ministry has two departments: the Environment Department and the Energy and Climate Change Department. These departments are responsible for the development of policy and regulatory framework, whilst the authorities and agencies have the responsibility to put these policies into practice.

The most important institutions for forest management are the forestry section within the Department of Environment and the Seychelles National Parks Authority (SNPA), with the mandate to manage, conserve, protect and exploit public forests in the Seychelles.

The Seychelles forestry sector is generally perceived as marginal, however, the indirect economic and environmental benefits of the sector are considerable. The amenity provided by the forests is extremely important for tourism and wood is an important raw material for handicraft industries, which have an important impact on employment. Moreover, the extremely vulnerable water supply is highly dependent on the forest vegetation cover. Forests have a significant role in preventing soil erosion and degradation caused by diverse phenomena, such as steep terrain, heavy rains, and land-use change. Timber production in the Seychelles is minor, therefore most timber products are imported to the Seychelles. According to FAOSTAT, the total import of wood products in 2018 amounted to 24 000 m^3.

The Seychelles is covered with 40 600 hectares of forest, representing 90 percent of the total land area, in fact, 75 percent of the land area (15 300 hectares) on the main three islands is covered by forests (**Table 2**) (FAO, 2014a). Forests in the Seychelles are often shrubdominated vegetation types and only partly closed forests, and include natural forests (ca. 88 percent) and plantations established for commercial purposes (ca. 12 percent).

TABLE 2.

LAND AREA BY VEGETATION TYPES

	ALBIZIA (HA)	MIXED (HA)	PLANTATION (HA)	COCONUT (HA)	BUSH (HA)	DEFORESTED (HA)	OTHER (HA)	TOTAL (HA)
MAHE	970	3 606	414	2 333	4 495	40	3 768	15 626
PRASLIN	30	1 222	51	61	1 364	273	798	3 798
CURIEUSE	0	111	20	10	121	30	0	293
LA DIGUE	10	394	0	91	273	0	253	1020
SILHOUETTE	414	404	0	434	606	0	162	2020
OTHER	0	18 788	4 444	0	0	0	10	23 232
ALL ISLANDS	1424	24 525	4 929	2 929	6 859	343	4 990	46 000

Source: FAO, 2014.

The Seychelles are famous for their indigenous rich biodiversity of endemic species, however, most of the forests currently have high percentages of exotic species. Only 2 000

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hectares of forest are classified as primary or climax forests and most of them are located on the Aldabra and the Silhouette islands. The forest ecosystem still offers a wealth of biological diversity and protects inland water ecosystems and important watersheds; around 50 percent of the forested areas are located within the protected areas (FAO, 2014a).

The mainland, including Mahé, Praslin and La Digue, has a forest area of roughly 6 700 hectares containing relevant timber resources (*Albizi*a forest, mixed forest, plantation forest). The bulk of the plantations are located on 'other islands' (4 464 hectares). Timber resources on these 6 700 hectares are to a large extent unused at present, mostly due to the lack of accessibility (steep or rocky areas as well as distance to roads) and protective regulations (river reserves, biodiversity hotspots) (UNIQUE, 2012). According to Global Forest Resources Assessment 2015 (FRA 2015), the growing stock is estimated at 3.1 million m^3. However, due to the large conservation areas and poor accessibility, it is estimated that only 0.7 million m^3 is accessible on the main islands (Ministry of Natural Resources and Tourism, 2001). Total wood removals in the Seychelles amount to 12 800 m^3 per year (u.b.), including 9 640 m^3 of industrial roundwood and 3 160 m^3 of woodfuel.

UNIQUE (2012) defined eight forest types in the Seychelles based not only on vegetation but also on the management aspects:

- plantation forests;
- semi-natural ***Albizia*** dominated forests;
- semi-natural high forests;
- river reserve forests, montane rainforests and other natural forests;
- semi-natural low forest and bushlands;
- coco de Mer dominated forests;
- degraded forest land;
- glacis vegetation and saxicolous forests.

Forests in the Seychelles are difficult to access which, together with the low productivity of both harvesting and processing, is causing high extraction costs for the feedstock. Practically all indigenous forest in the Seychelles is mixed with introduced plant species. There are 600-700 species of introduced plants in the Seychelles, but not all of these plants spread naturally through the forest habitat and therefore do not compete with the indigenous plants. The two most serious threats appear to be ***Albizia*** and cinnamon (Ministry of Natural Resources and Tourism, 2001).

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3.3 WASTE MANAGEMENT

The Landscape and Waste Management Agency (LWMA) is an agency operating under the MEECC. The agency is in charge of organising cleaning of public spaces and waste collection. Furthermore, it also administers waste management contracts for waste collection and landfill management. Currently, LWMA administrates two sets of agreements that include financial flows, that is, agreements with commercial establishments, and agreements with contractors for waste collection and treatment.

In 1997 the service of municipal waste collection, treatment, disposal of solid waste and operation of the landfill on Mahé was awarded to the Société de Traitement et d'Assainissement Régionale (STAR). However, in 2019 the system was changed and the municipal waste collection on the three main islands was divided into ten zones. LWMA has tendered ten concessions for collection of municipal waste for ten different zones: seven on Mahé, two on Praslin, and one on La Digue. Eight contractors have signed a six-year contract with LWMA and are paid on a monthly basis (COWI, 2019).

With respect to commercial waste, the commercial establishments are required to pay LWMA according to the quantity and composition of their waste. Commercial waste is currently collected by contractors who either have or do not have a contract with LWMA. At the moment, there are 19 contractors for the collection of commercial waste. Those who have a contract with LWMA are paid by LWMA and do not pay a tipping fee. The other group of contractors do pay a tipping fee according to the estimated quantity and composition of the waste. This system is expected to change in the future and commercial establishments will enter into direct agreements with waste collectors, while the role of LWMA will be that of the regulator and supervisor only (COWI, 2019).

There are four disposal sites in operation in the Seychelles, two on Mahé (Providence and Ansé Royale), one on Praslin (Amitié) and one on La Digue (L'Union).

The Providence landfill is divided into an old (I) and new (II) part. The old part has been in operation since around 1996 and does not have a bottom liner. In 2016, landfilling at Providence I officially stopped and moved to a new, adjacent

site (Providence II). However, small amounts of liquid waste are still disposed of and, the site has never been properly rehabilitated. The area of Providence II covers 7.9 hectares and the landfill is estimated to have a remaining lifespan of 15 years. The new site is constructed as a sanitary landfill and includes drainage channels for the collection of landfill leachate, as well as a pre-treatment facility.

The Anse Royale landfill has rarely been used due to public opposition and at the moment only accepts small amounts of inert waste (glass and incinerator ash).

Amitié is a non-engineered (no liner, no leachate collection, no landfill gas management) dumping site on Praslin that has been in operation for more than 20 years. There is a simple registration and payment system at the gate, but no weighbridge. There are separate zones for various waste streams (e.g. organic, metals, mixed waste), but in practice this is not fully adhered to. The site is managed by LWMA,

who has subcontracted the daily operation to "BS Excavation".

The L'Union landfill on La Digue was the Seychelles' first operational sanitary landfill, built in 1998. It has a leachate collection and evaporation/recirculation facility, but this is currently out of function. There are three areas on site for different waste streams: 1) mixed waste; 2) metal waste (including e-waste); and 3) green waste. The site is only open two days a week and no registration is required at the gate (COWI, 2019).

At the moment all major fractions of waste, with the exception of PET, aluminium cans, and large scrap metal, are only being landfilled. Landfilling poses environmental problems including, leaching of pollutants, methane emissions, and resource depletion. Furthermore, because land is scarce and expensive in the Seychelles, landfilling will incur significant costs to the government in the future.

A significant challenge for waste management in the Seychelles is scale. Due to the small population of the country, there is little capital available to support waste management projects, particularly to stimulate recycling initiatives or advanced waste treatment. Additionally, the low volume of total waste generated provides insufficient quantities for technically feasible treatment systems. The small economies of scale prevent waste businesses from generating revenues to overcome operation and investment costs (Lai *et al.*, 2016).

Moreover, waste generation in the Seychelles has increased recently due to economic development, population growth and tourism, and estimates suggest that this will continue in the future. Population has been increasing, from around 90 thousand in 2010 to current 98 thousand inhabitants. In 2018, 349 861 visitors came to the Seychelles, consequently, tourism makes a significant contribution to waste generation.

Waste generation has been increasing and currently around 70 000 tonnes of waste are delivered to the Providence landfill annually. An additional 10 500 and 1 100 tonnes are delivered to the landfills on Praslin and La Digue respectively.

TABLE 3.

OVERVIEW OF DIFFERENT WASTE CLASSES AT MAHÉ WEIGHBRIDGE

WASTE CLASS	WASTE TYPE	WASTE CONTENT	SHARE
1	MSW	GREEN & KITCHEN, 48 PERCENT; MISC. COMBUSTIBLE, 11.1 PERCENT; MISC. NON-COMBUSTIBLE, 9.4 PERCENT; PLASTIC FILM, 6.7 PERCENT; CARD & PAPER, 5.9 PERCENT; GLASS, 5.2 PERCENT; METAL CANS, 3.9 PERCENT; TEXTILES, 3.1 PERCENT; ELECTRONICS, 1.7 PERCENT; OTHER PLASTICS, 1.6 PERCENT; PLASTIC BOTTLES, 1.6 PERCENT	33 PERCENT
2	COMMERCIAL	WASTE COLLECTED FROM COMMERCIAL, INDUSTRIAL AND TOURISM BUSINESSES	12 PERCENT
3	GREEN	VEGETATIVE MATTER FROM LITTER BINS AND PRIVATE TRUCKS	2 PERCENT
4	LIQUID	MOSTLY SLUDGE FROM I.O.T INDUSTRIAL FACTORY	14 PERCENT
5	MIXED	UNSORTED WASTE BROUGHT BY PRIVATE TRUCKS	36 PERCENT
6	METAL	FERROUS AND NON-FERROUS METAL	1 PERCENT
7	PUTRESCENT	REMAINS OF ANIMALS FROM ABATTOIRS	2 PERCENT
8	WASTE OIL	WASTE OILS FROM HOTELS, RESTAURANTS, GARAGES, PORTS (BOATS)	<1 PERCENT
9	INERT WASTE	CONTAINS MOSTLY GLASS AND UN-POWDERED ASBESTOS	<1 PERCENT
10	HAZARDOUS	INCLUDES BATTERIES, MEDICINES, EXPIRED GOODS, REAGENTS ETC	<1 PERCENT
11	OTHER	ASHES, SAWDUST, ETC.	UNKNOWN

Source: Lai ***et al.****, 2016.*

STAR used 11 classes for their waste collection system to conduct its annual assessments of waste landfilled on Mahé. Waste classes and their shares are presented in **Table 3**. It can be seen that green and kitchen waste creates almost 50 percent of the municipal solid waste (MSW). By implementing an adequate sorting scheme either at the household level or district level, much of this waste could be diverted from the landfill and recycled either locally (e.g. paper waste, tyres, glass) or exported overseas for processing (e.g. scrap metal, batteries, oil). As a significant share of the solid waste is biodegradable, separation of this fraction would substantially contribute to diversion of waste from landfills (Talma and Martin, 2013).

3.4 METHODOLOGY

The objective of the natural resource assessment is to estimate the quantity of agricultural residues, forest feedstock and biodegradable waste that is potentially available for energy production, as well as indicate their accessibility. The analysis is helpful for identifying the main residues and waste types available for bioenergy production as well as their geographical distribution.

The analysis for the Seychelles focused on primary crop residues, livestock residues (mainly pig and chicken manure), forest feedstock (additional forest harvesting and forest harvesting residues) and biodegradable waste.

The assessment was conducted following the bioenergy and food security approach, more specifically the Bioenergy and Food Security (BEFS) methodology (FAO, 2014b). The feedstock analysed have varying uses from country to country and from region to region within a country. For instance, many crop residues are used as soil amendment or as bedding material while livestock residues, primarily manure, is used as organic fertilizer. As a result, the use of different feedstock for bioenergy production must be done so as to avoid negative impacts on any of the existing uses. Feedstock accessibility will depend on feedstock quantities and geographical distribution, as it is more cost-effective to collect the feedstock concentrated in certain areas, but also on factors such as topography, available infrastructure (e.g. roads, railways) and labour.

This assessment; therefore, follows three levels of analysis:

1. Production is the amount of feedstock produced every year.
2. Availability is the amount of feedstock that is potentially available for bioenergy production after deducting all other, current competing uses from the total production of feedstock.
3. Accessibility is the amount of feedstock that can practically be mobilised for bioenergy production.

The successful completion of the three levels of analysis is dependent on the availability of specific information. A more detailed description of the steps of the analysis is provided in the following sub-sections.

3.4.1. Crop residues

Crop residues are the organic material produced as by-products from harvesting and processing of agricultural crops. They can be further categorized as primary and secondary residues.

1. Primary residues are those generated in the field at the time of harvest. They can then be collected in the field, such as cereal straw (when baled) or can be spread in the field, as is the case with sugarcane tops, cotton and maize stalks.
2. Secondary residues are those that are co-produced during processing. These include paddy husk, bagasse, maize cob, coconut shell and coconut husk. Secondary residues are collected at a processing facility.

STEP 1: PRODUCTION OF CROP RESIDUES

The amount of crop residue produced depends on the:

- main crop production;
- crop specific residue to crop ratio (RCR).

The initial selection of crops and related crop residues to be analysed in the assessment was based on two criteria:

- the scale of production of the specific crop; and
- the suitability of their residues to produce briquettes and pellets as well as to be used as feedstock for direct combustion, cogeneration of heat and power (CHP) and/or biogas technologies.

The scale of production, which included the amount (tonnes) of crops produced and the corresponding harvest area (hectares) for the Seychelles, was taken from the FAOSTAT database and compared with the Seychelles Census of Agriculture 2011. A five-year average (2014-2018) was used as the basis for the analysis to reduce uncertainty due to annual changes in production volumes.

Based on the five-year average crop amount produced, the total amount of crop residues produced was calculated using the following equation:

CRtot = CP * RCR

Where:

CRtot [t/year] = total crop residues produced in the area

CP [t/year] = average crop production in the area

RCR = residue to crop ratio of the specific crop

The values of RCR used for the analysed crops were obtained through a literature review.

STEP 2: AVAILABILITY OF CROP RESIDUES

The CRtot quantifies the total amount of crop residues produced. However, not all residues produced are available for use as feedstock for bioenergy production. Agricultural residues are highly important sources of biomass for both the domestic and industrial sectors and

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hence are used for various purposes, such as soil amendment and as animal feed. Therefore, the availability of residues for energy application can vary significantly depending on current uses, which can then also vary substantially across regions.

The bioenergy residue potential is the quantity of residues that can be used to produce bioenergy without affecting other sectors where residues are already used. This can be calculated using the following equation:

CRav = CRtot - Crsoil - CRused

Where:

CRav [t/year] = crop residues available for bioenergy production in the area

CRtot [t/year] = total crop residues produced in the area

CRsoil [t/year] = amounts of residues that should be left in the field

CRused [t/year] = amounts of crop residues already used

The amounts of residues that should be left in the field depends on the soil type and structure (content of soil organic carbon, nutrients), topography, climate, level of inputs (chemical, organic fertilizers), agricultural practice (crop rotation, tillage) and the crop cultivated. The amounts of residues used for other purposes depends on the availability of other resources, activities and the socio-economic conditions of the population in the area.

STEP 3: ACCESSIBILITY OF CROP RESIDUES

Even when large amounts of crop residues are available, collecting and mobilising them for bioenergy production can be challenging. Hence, the concept of accessibility, which aims to identify the proportion of available crop residues that can actually be used for bioenergy production, is important.

The accessibility of residues relies heavily on their location. Primary residues that are spread in the field are difficult and costly to collect. For this reason, they are the preferred option, as opposed to collected residues, for soil amendment and as mulch, which helps to conserve moisture, improves the fertility and health of the soil. Those residues that are primarily collected in the field and are baled, such as straw, have relatively high accessibility. Secondary residues are usually available in relatively large quantities at the processing site and may be used as an energy source for the same processing plant, and involve minimal transportation and handling costs. For example, these residues include rice husks, maize cob, and sunflower head. The accessibility of residues also depends on the logistical infrastructure such as road and rail network, which has a significant impact on collection and transportation costs. In theory, the accessibility of residues can be calculated using the following equation:

CRac = CRav * k

Where:

CRac [t/year] = crop residues accessible for bioenergy production in the area

CRav [t/year] = crop residues available for bioenergy production in the area

k[percent] = accessibility coefficient

The accessibility coefficient is determined by a number of parameters, such as the harvesting method and type of machinery used (if any), labour availability for residues collection, existence and type of transport infrastructure, and the existence and size of storage facilities in the area. The accessibility of residues is fundamental to determining the optimal location of where to place a bioenergy facility and its economic viability.

3.4.2. Livestock residues

Manure is a by-product of livestock production and can be used for energy production with minimal pre-treatment. In AD, animal manure and slurries are used for simultaneous production of biogas (renewable fuel) and digestate (valuable biofertilizer). The main livestock types assessed in the report are pigs, poultry and cattle.

The amount of manure produced depends on several factors including animal type (ruminant or non-ruminant), diet (forage-based or grain-based), animal age (which can influence the amount of feed consumed), and animal productivity as well as other factors.

STEP 1: PRODUCTION OF LIVESTOCK MANURE

Total manure production is based on the type and number of animals (pigs, poultry or cattle), and manure produced per head per year.

As regards pig and cattle, it is also important to know the breed, age and gender of the animal, while for poultry a distinction needs to be made between layers and broilers.

The amount of manure produced was calculated using the following equation:

LRtot = Nan * Mph

Where:

LRtot [t/year] = total manure produced per year in the area

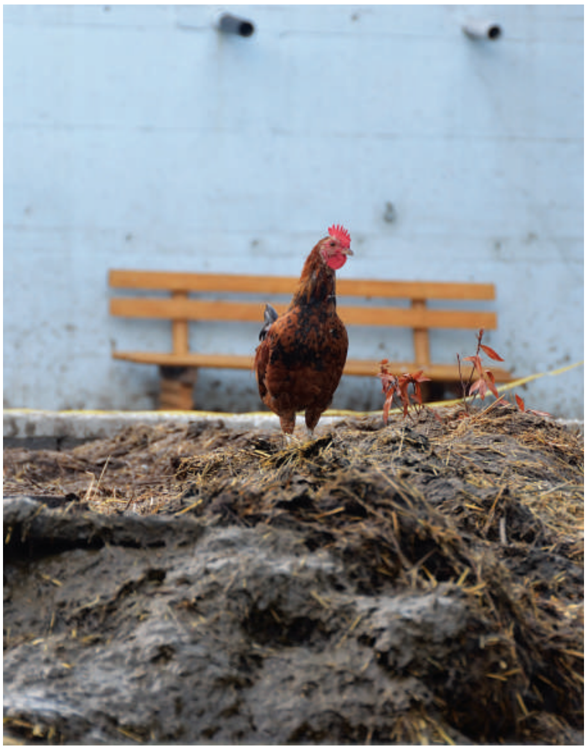
Nan [t/year] = number of animal (per pig, cattle and poultry type) in the area

Mph [t/year] = amount of manure produced per head per year

Values from BEFS RA were used for the value of manure produced per head for each type of livestock.

STEP 2: AVAILABILITY OF LIVESTOCK MANURE

Manure is a valuable raw material that can be used as a source of organic matter and fertilizer for crop and pasture production. The share of manure used as biofertilizer can vary substantially from country to country or region to region. Nevertheless, digestate (by-product of AD) can also be used as valuable bio-fertiliser. It even has some advantages over the use of fresh manure, although it contains less organic matter that has been used for biogas production. In order to assess the current use of manure and its availability for bioenergy production in the Seychelles, several larger livestock farmers were interviewed using a livestock residues questionnaire.



STEP 3: ACCESSIBILITY OF LIVESTOCK MANURE

Accessibility of livestock manure depends largely on the size of animal holding as well as the systems of manure management. The type of manure storage and handling systems is important to efficiently collect and utilize the produced manure. Manure collection systems are dependent on many factors such as bedding type and the system of rearing. Furthermore, they require substantial financial investment. A large farm could possibly be in the position to invest in a sophisticated manure management system that makes manure collection; as a result, its accessibility would be high.

3.4.3. Forest feedstock

Forests are the main source of woodfuel, used for energy generation as fuelwood (firewood) or for other types of woody biofuels (briquettes, pellets, chips). In addition, forests provide a multitude of benefits to humans (ecosystems services) in terms of water supply and regulation, habitat for biodiversity, erosion control, climate regulation, recreation and many others.

The aim of the assessment was to evaluate the potential of additional forest harvesting and forest harvesting residues for the production of bioenergy.

3.4.3.1. Additional forest harvesting

One of the main principles of sustainable forest management is to maintain the stability of the ecosystem services they provide. Along with this principle, in order to sustain the productivity and sustainable supply of products, the rate of wood harvesting should not be higher than its production rate over time.

The assessment of the potential of additional forest harvesting should, at least, be based on trends in the extent of forest area and growing stocks. A decrease in the forest area over time may indicate unsustainable forest management, while the gradual increase in a forest area may indicate the potential for additional forest harvesting for energy. However, the assessment of sustainability of additional forest harvesting should include information on the growing

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stocks, forest composition and preservation of ecosystem services as well.

As this particular feedstock is not currently being used, it would be available for energy production. Nevertheless, its accessibility will largely depend on the feedstock location, as well as the available infrastructure and morphology of terrain. Therefore, a more detailed and spatially explicit analysis is required to estimate this potential.

3.4.3.2. Forest harvesting residues

Forest harvesting residues are parts of felled trees that have not been removed from the forest. The rate of removal varies among forests and usually depends on the end product that will be made and the cost-effectiveness of removing the tree. In the case of industrial roundwood, upper logs, branches and different cut-offs are often left in the forest, while stems are removed. Occasionally stems are debarked in the forest. The rate of felling removal for woodfuel is usually higher than that of industrial roundwood, as the smaller branches, cut-offs and bark can be used as fuelwood or for production of briquettes, pellets or chips.

The assessment of the bioenergy potential from harvesting residues was based on the annual roundwood production. Assuming that tree foliage, small branches and stumps are left in the forest for soil fertilization and protection and biodiversity conservation. Residues were divided into three groups: branches and various cut-offs, foliage and bark, and the calculation was conducted using the default factors from BEFS RA on rate of felling removal and tree composition.

STEP 1: PRODUCTION OF FOREST HARVESTING RESIDUES

To assess the amount of forest harvesting residues produced, following data was required:

- annual production of industrial roundwood (m^3/year);
- annual production of woodfuel (m^3/year);
- rate of felling removal (percent);
- representative tree composition (ratio of crown-stem, foliage-crown, bark-stem) in the predominant forest type.

STEP 2: AVAILABILITY OF FOREST HARVESTING RESIDUES

The quantity of branches and various cut-offs and bark available for bioenergy is calculated by subtracting the total amount of forest harvesting residues by the portion already collected and used. Assuming that foliage will be left in the forests for soil fertility and biodiversity conservation, it is therefore not considered as a potential resource for energy production.

STEP 3: ACCESSIBILITY OF FOREST HARVESTING RESIDUES

The percentage of the harvesting residues that can be collected should reflect the site characteristics (taking into consideration infrastructure, topography), the practicality of the collection (size of branches and cut-offs), in addition to the machinery and labour availability.

3.4.4. Biodegradable waste

A wide range of biomass wastes can be used as feedstock for the production of biogas via AD. These would mostly include organic wastes from food and agro-industries, organic fraction of municipal waste and catering waste and sewage sludge. AD is a microbiological process of decomposition of organic matter in the absence of oxygen. The main products of AD are biogas and digestate. Biogas is used for the production of energy, while digestate, depending on its composition can be used as fertiliser. On the other hand, organic feedstock, such as garden and park waste that contain high proportions of lignocellulosic material, are better suited for composting, as pre-treatment is necessary in order to be used for AD.

Source-separated organic waste refers to the organic fraction of waste, such as food waste, the organic fraction of MSW and other similar organic wastes, separately collected. The separate collection of wastes can provide high-quality feedstock for AD, while at the same time reduce the stream of organic materials going to landfills and incineration in favour of recycling and nutrients recovery. Separate collection is an integral part of the overall waste management system that ensures the high quality and purity necessary for their optimal use as AD feedstock. Compared to source separation, mixed collection followed by a central separation implies higher costs and considerable losses of organic matter as well as high contamination risk. The main limitation of separate collection of organic waste as feedstock for AD is considered to be the apparently high cost of waste collection (Wellinger ***et al.***, 2013).

Waste feedstock can be quite diverse. Waste types differ in their characteristics, such as dry matter content, C:N ratio and biogas yield, therefore knowing the composition of waste is indispensable for estimating the potential of AD for biogas production and running a biogas plant.

STEP 1: PRODUCTION OF BIODEGRADABLE WASTE

- amounts [t/year] produced per each waste category

The initial selection of waste categories to be analysed in the assessment was based on two criteria:

- the scale of production of the specific waste type; and
- the suitability of each waste type for AD and biogas production.

STEP 2: AVAILABILITY OF BIODEGRADABLE WASTE

Not all produced biodegradable waste would be available for bioenergy production, that is, some organic wastes might already be used for composting or as feed for animals. Therefore, the amount of waste available for bioenergy is

calculated by subtracting the total amount by the portion already used.

STEP 3: ACCESSIBILITY OF BIODEGRADABLE WASTE

Waste collection and its mobilisation for bioenergy production can be challenging, thus it is important to estimate the proportion of waste that can be collected and used for energy production. Accessibility of waste residue depends largely on:

- the waste management system, for example, whether organic wastes are collected separately;
- location: dispersed production, such as in the case of household wastes, or localised production (food processing plants, or lager hotels);
- available infrastructure and labour.

3.5 RESULTS

TABLE 4.

CROP PRODUCTION IN THE SEYCHELLES

CROP	PRODUCTION (TONNES/YEAR)	AREA (HA)	YIELD (TONNES/HA)
COCONUTS	2 512	547	4.6
BANANAS	1 983	97	20.4
TOMATOES	458	68	6.7
CASSAVA	228	19	12.3
MANGOES, MANGOSTEENS, GUAVAS	67	8	8.8
LEMONS AND LIMES	55	3	18.3
ORANGES	44	4	10.9
PINEAPPLES	40	3	15.4
TEA	18	38	0.5
AVOCADOS	13	1	13.0
VEGETABLES, FRESH NES	2 817	681	4.1
FRUIT, FRESH NES	399	14	29.4
FRUIT, TROPICAL FRESH NES	280	47	5.9

Source: FAOSTAT, 2020.

3.5.1. Crop residues

STEP 1: CROP RESIDUE PRODUCTION

The quantity of crop residues produced per year depends on the amounts of crops harvested in a given year. In order to maximise the accuracy of the estimation, the average quantity of crops produced per year was calculated based on the annual production quantity between 2014 and 2018 according to FAOSTAT. The five-year average was then used to calculate the amounts of residues produced. The FAOSTAT data were crosschecked with the data from the Seychelles Agricultural Census (2011) for consistency. **Table 4** details the five-year average of the quantity produced, harvest area and yield for all the crops that were initially selected for the analysis.

Based on the data available, the scale of production of the specific crop and the suitability of their residues for bioenergy production, a further analysis was conducted for bananas, coconuts and cassava residues. The RCR values were obtained from a literature review and from BEFS RA. RCR were used to estimate the total production of residues for each crop (**Table 5**).

The quantity of crop residues produced in the Seychelles were obtained by multiplying crop production (tonnes/year) with RCR. Total crop residues amounted to 8 911 tonnes/year, while the largest share were bananas residues (**Table 5**).

TABLE 5.

PRODUCTION OF CROP RESIDUES SUITABLE FOR BIOENERGY PRODUCTION

CROP	RESIDUE	RCR	QUANTITY (TONNES/YEAR)
BANANAS	PSEUDOSTEM / FALSE TRUNK	2.25	4 462
	LEAVES	0.24	476
	PEELS	0.25	496
COCONUTS	FRONDS	0.47	1 180
	HUSK	0.49	1 231
	SHELL	0.39	980
CASSAVA	STALK	0.13	30
	PEELS	0.25	57
TOTAL			8 911

Source: elaboration based on BEFS assessment results, 2020.

STEP 2: AVAILABILITY OF CROP RESIDUES

While the production trends of crops provide a general overview of the amount of crop residues produced, this does not define the potential availability to produce bioenergy. The volume of residues that can be used sustainably for energy generation depends on the current uses of the residues. They are spread across the field to prevent soil erosion by wind or water. Furthermore, they provide organic matter and nutrients thereby enhancing soil fertility or can be used for other purposes such as feed and bedding for livestock.

Information on the current uses of selected crop residues for the Seychelles was not available, therefore only the share of crop residues that should be left in the field was taken into consideration. The volume of residues that should be left in the field depends on the soil type and structure, climate, management practices and existing conservation practices. As country specific information was not available, the default value of 25 percent of crop residues that should be left in the field was used for the residues generated in the field (primary residues). This value represents an estimation based on a literature review, which can be applied globally and ensure sustainability of agricultural production. For the residues generated at a processing plant (secondary residues) the default value is set at zero percent. Namely, it is assumed that it would not be cost-effective to return the residues back to the fields.

Table 6 summarizes the estimated amounts of residues potentially available for bioenergy production at the national level.

TABLE 6.

CROP RESIDUES AVAILABILITY FOR BIOENERGY PRODUCTION

CROP	RESIDUE	TOTAL PRODUCTION (TONNES/YEAR)	TYPE	AVAILABILITY FOR BIOENERGY (PERCENT)	QUANTITY AVAILABLE FOR BIOENERGY (TONNES/YEAR)
BANANAS	PSEUDOSTEM / FALSE TRUNK	4 462	SPREAD	75 PERCENT	3 346
	LEAVES	476	SPREAD	75 PERCENT	357
	PEELS	496	COLLECTED	100 PERCENT	496
COCONUTS	FRONDS	1 180	SPREAD	75 PERCENT	885
	HUSK	1 231	COLLECTED	100 PERCENT	1 231
	SHELL	980	COLLECTED	100 PERCENT	980
CASSAVA	STALK	30	SPREAD	75 PERCENT	22
	PEELS	57	COLLECTED	100 PERCENT	57
TOTAL					7 374

Source: elaboration based on BEFS assessment results, 2021.

STEP 3: ACCESSIBILITY OF CROP RESIDUES

It should be noted that all of the residues potentially available for use as feedstock for bioenergy production might not be accessible. The accessibility of residues depends on various factors including the location of residues (field vs processing plant). The collection and mobilisation of residues depends on infrastructure such as road density as well as access to specific collection machinery. Primary crop residues are generally not collected with the crop and are spread in the field. In certain cases, they may be partially collected for further use locally. Secondary residues are generated at the agro-processing facility and hence are less expensive and easier to mobilise. There is a fundamental difference between the accessibility of primary residues, which are difficult to mobilise, and secondary residues, which can easily be mobilised.

The secondary residues that are collected in agro-processing industries are therefore more economical when used as feedstock for bioenergy generation. Nevertheless, the net availability of primary residues that are spread in the field is substantially larger than the collected residues, thus making them more lucrative for bioenergy production. However, the collection of residues from fields can be costly and depends on the type and availability of harvesting machinery, as different residue types require different collection methods and machinery.

The size of agricultural holding is also important since, in areas where agriculture exists in relatively small fields, primary residues tend to be scattered across many fields making them more difficult to collect, store and mobilise. In addition, the distribution and size of the agricultural holdings will have an impact on the location of the bioenergy power plant as well as the transportation cost of the feedstock.

It is therefore essential to understand the accessibility of residues at the site where the assessment is being carried out, in order to accurately predict the technical potential to produce bioenergy from agricultural residues.

Due to the minor cassava production and small farm size in the Seychelles (average farms size is 0.8 hectares, rarely exceeding 2 hectares) cassava residues are considered difficult and costly to collect, store and mobilise for bioenergy production. Moreover, cassava residues can be used for other purposes (e.g. feed) and might already be partly or fully utilised. Coconuts are mostly produced on the outer islands such as Coetivy, Desroches and Poivre (Moustache, 2011). The major constraints for obtaining this biomass from the outer islands would be the availability of local labour and high transportation costs. Therefore, only banana residues were considered to be accessible and were further considered for bioenergy production (**Table 7**). However, the true accessibility of banana residues depends on their location, the feasibility and cost of their collection and transportation, and this information was not available for the assessment. The total quantity of banana residues that could be accessible for bioenergy amounts to 4 199 tonnes per year, with false trunks representing almost 80 percent of all residues.

TABLE 7.

CROP RESIDUES ACCESSIBILITY FOR BIOENERGY PRODUCTION

CROP	RESIDUE	QUANTITY (TONNES/YEAR)
BANANA	PSEUDOSTEM / FALSE TRUNK	3 346
	LEAVES	357
	PEELS	496
TOTAL		4 199

Source: elaboration based on BEFS assessment results, 2020.

3.5.2. Livestock residues

STEP 1: PRODUCTION OF LIVESTOCK MANURE

The commercial livestock sector in the Seychelles is dominated by some large producers, particularly pig farmers and poultry farmers (both layer and broiler farms). Local livestock production has been declining since 2006 due to the trade liberalization of meats and meat products. In April 2010 the government totally liberalized the importation of meats and meat products. It was believed that by liberalizing the imports, the average consumer would be able to benefit from the lower prices of imported products. Consequently, competition from the significantly lower cost imports forced many local livestock farmers to close down their production units (Ministry of Fisheries and Agriculture, 2015).

As a first step, the total manure produced in the Seychelles was estimated. The method used to estimate the total manure production is based on the number of animals (pig, poultry, and cattle) and manure produced per head. By multiplying the number of heads with the manure per head for a specific type of livestock, the total amount of manure that is produced was estimated.

The quantity of manure produced per animal can vary depending on parameters such as the breed, age, and gender of the animal. It should also be noted that where livestock manure is being considered for biogas production, the physical and chemical properties of the manure are critical. The content of total solids (TS) and volatile solids (VS) of the manure have a large impact on potential biogas production. The TS and VS content in manure also depends on the feeding profile of the livestock.

An important aspect of chicken manure is the distinction between layer and broiler manure. Broiler manure is generally mixed with litter and hence less suitable for biogas production. Therefore, preference is generally given to layer manure for biogas production.

Data on livestock farms, livestock numbers, and animal types were obtained from the Seychelles Agricultural Agency. Additionally, data were updated through interviews conducted with larger farms (**Table 8**).

TABLE 8.

LIVESTOCK FARMS

LIVESTOCK TYPE	NUMBER OF FARMS	LIVESTOCK NUMBER (HEADS)
PIGS	26	4 597
LAYERS	7	75 600
BROILERS	9	147 000
CATTLE	2	170

Source: Seychelles Agricultural Agency, 2020.

TABLE 9.

LIVESTOCK MANURE PRODUCTION

LIVESTOCK TYPE	LIVESTOCK NUMBER (HEADS)	MANURE GENERATION (KG/ HEAD DAY)	TOTAL MANURE PRODUCTION (TONNES/YEAR)
PIGS	4 597	2.5	4 195
LAYERS	75 600	0.036	993
BROILERS	147 000	0.036	1 932
CATTLE	170	5.0	310
TOTAL			**7 430**

Source: elaboration based on BEFS assessment results, 2020.

BEFS RA values for daily manure production per livestock type were used to estimate total manure production (**Table 9**).

Based on the number of animals and coefficients for daily manure production per head, the total manure produced in the Seychelles per year was calculated (**Table 9**). The total manure produced amounted to 7 430 tonnes per year. Most of the manure was pig manure (56.7 percent) and chicken manure (39.4 percent).

Figure **15** shows the geographical distribution of manure production in the Seychelles. Most of the manure was produced in Baie Lazare (2 557 tonnes/year), Anse Boileau (1 164 tonnes/year) and Plaisance (840 tonnes/year) districts of Mahé.

STEP 2: AVAILABILITY OF LIVESTOCK MANURE

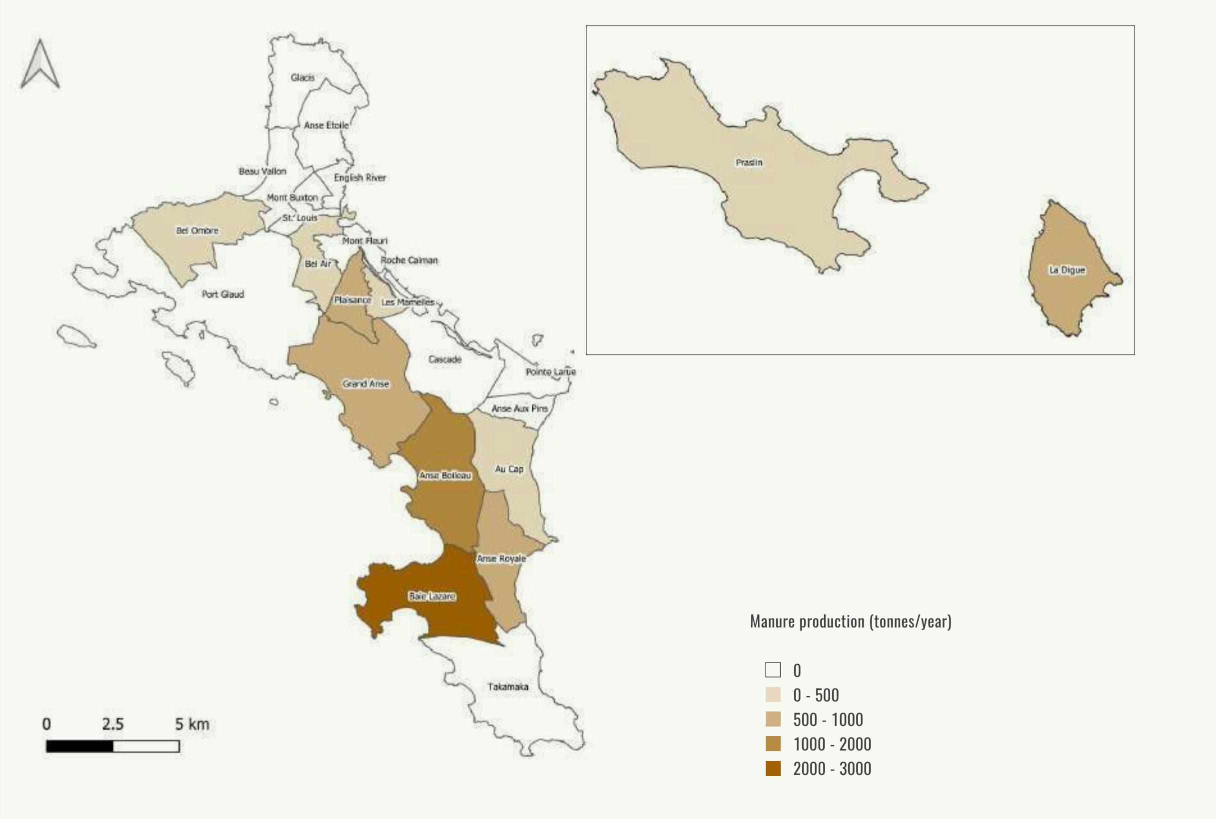
Livestock manure is an important source of organic matter and is often used as soil amendment. It can moreover be used for other purposes, such as solid fuel. The amount of livestock manure available for bioenergy production depends on its current use, such as in the case of crop residues. Based on the information obtained from the farms, livestock manure in the Seychelles is predominately sold as a fertiliser or used directly in the fields by the farmers. It should be noted that when manure is used to produce biogas through AD, the resulting digestate can still be used as a fertiliser. Digestate still contains all of the nutrients, and therefore has a minimal impact on the current use of the manure. On the other hand, digestate has less organic matter than fresh manure, as part of the organic matter has been used to produce biogas. Nevertheless, this easily degradable fraction would be the most quickly decomposed and lost from the soil. If manure were not mixed with other biodegradable feedstock that prevent the use of digestate as fertiliser, the total manure produced in the Seychelles would feasibly be available for bioenergy production.

STEP 3: ACCESSIBILITY OF LIVESTOCK MANURE

Accessing and mobilising livestock manure can pose a challenge, consequently, it is essential to examine the accessibility of manure to understand the quantity of the manure that can feasibly be mobilised for energy production. Animal manure can be made available as a liquid (farm slurry) or in a more solid form. The accessibility of manure can vary significantly, depending on management practices.

FIGURE 15.

GEOGRAPHICAL DISTRIBUTION OF MANURE PRODUCTION IN THE SEYCHELLES



Source: elaboration based on BEFS assessment results, 2020.

It can be collected centrally from stables if intensive livestock rearing systems are applied, while it is almost impossible to collect manure in extensive systems where it is left in the pastures. In addition to livestock production systems, the size of farms is an important parameter that determines the accessibility of livestock manure. Larger farms with more animals allow for the collection of large quantities of manure from the one site, whereas smaller farms would have lower quantities of manure. Therefore, more farms would need to be visited in order to obtain the same quantity of manure.

Larger farms in the Seychelles are predominantly producing livestock in intensive systems and are already collecting animal manure either to sell or for to use on the agricultural land. Manure accessibility will depend on the size and location of a farm in addition to the transportation costs. The transportation of manure from other islands to Mahé might not be economically viable. Nevertheless, the majority of pig manure (77.3 percent), layer manure (91.4 percent), boiler manure (82.3 percent), and cattle manure (82.4 percent) are produced on Mahé, amounting to 5 995 tonnes per year (**Table 10**).

TABLE 10.

LIVESTOCK MANURE PRODUCED ON MAHÉ

LIVESTOCK TYPE	LIVESTOCK NUMBER (HEADS)	MANURE GENERATION (KG/HEAD DAY)	TOTAL MANURE PRODUCTION (TONNES/YEAR)
PIGS	3 550	2.5	3 241
LAYERS	69 100	0.036	908
BROILERS	121 000	0.036	1 590
CATTLE	140	5.0	256
TOTAL			**5 995**

Source: elaboration based on BEFS assessment results, 2020.

Most of the manure was pig manure (54.1 percent) and chicken manure (41.7 percent). 94.9 percent (5 687 tonnes per year) of this manure was produced in larger farms (> 80 pigs, > 8 000 chicken and one farm with 140 cattle).

3.5.3. Forest feedstock

3.5.3.1. Additional forest harvesting

STEP 1: FEEDSTOCK PRODUCTION FROM ADDITIONAL FOREST HARVESTING

According to FRA 2015, the forest surface area and growing stock in the Seychelles have been stable since 1990, amounting to 40 666 hectares and 3.1 million m³ respectively. Total wood removals

have increased slightly from 10 100 m^3/year in 1990 to 12 800 m^3/year in 2018. This includes 9 680 m^3/year of industrial roundwood and 3 160 m^3/year of woodfuel (FAO, 2014a; FAO, 2020).

The most important reason for sustainable forest management and the preservation of forest areas in the Seychelles is not timber production but rather the provision of ecosystem services, such as biodiversity conservation, erosion, and watershed protection. Therefore, most of the forest types mentioned in UNIQUE (2012) should not be further exploited for bioenergy purposes as they are already being used for other ecosystem services (e.g. timber, tourism), or they should be conserved or actively enriched. Additional harvesting of plantation forests, semi-natural *Albizia* dominated forests and semi-natural high forests were considered as a potential source of feedstock for bioenergy. Plantation forests are already being utilised for timber production, while during technical consultations implemented in the Seychelles it was concluded that semi-natural high forests should not be further exploited for bioenergy production.

On the other hand, *Albizia (Falcataria moluccana)*, an exotic species, is frequently considered to be a deterrent to forest management objectives, for example, the implications for biodiversity due to invasiveness and allegedly high-water consumption. The red timber subspecies of *Albizia* is sometimes used for timber (e.g. construction, rafters), but its use as timber has declined due to its lower quality. *Albizia* forests also provide various ecosystem services, such as erosion control, nutrient fixing, soil improvement, and aesthetic value. Therefore, a feasible option would be to use this feedstock for the production of bioenergy at the level of annual increment, provided no biodiversity hotspot is present. In this way, these forests would continue to provide ecosystem services but their further spreading could be controlled.

There are around 1 000 hectares of semi-natural *Albizia* forests on Mahé (UNIQUE, 2012). *Albizia* occupy much smaller areas on Praslin (30 hectares) and La Digue (10 hectares); most of the Silhouette Island is a national park with 414 hectares of *Albizia* forests (FAO, 2014a). Consequently, only the *Albizia* forests on Mahé were taken into consideration for additional harvesting. The mean annual increment (MAI) for this forest type is 10 m^3/hectares on poor and 30 m^3/hectares on the best sites (UNIQUE, 2012). Based on an average annual increment of 20 m^3/hectares, it was estimated that around 20 000 m^3 of this feedstock is produced per year on Mahé.

STEP 2: AVAILABILITY OF FEEDSTOCK FROM ADDITIONAL FOREST HARVESTING

As this feedstock is not currently used, it would be available for bioenergy production assuming that the entire annual increment can be

harvested. Of course, this will also depend on the accessibility of feedstock.

STEP 3: ACCESSIBILITY OF FEEDSTOCK FROM ADDITIONAL FOREST HARVESTING

Accessibility of this feedstock, which is a crucial factor due to the topography (steep slopes or rugged areas), could not be estimated due to the lack of information on the distribution of *Albizia* forests on Mahé. The accessibility will also depend on the protective regulations (river reserves, biodiversity hotspots), distance to roads, feasibility of harvesting, and economic viability of bioenergy production.

3.5.3.2 Forest harvesting residues

STEP 1: PRODUCTION OF FOREST HARVESTING RESIDUES

It was assumed that forest harvesting residues in the Seychelles would be produced in plantation forests that are harvested for timber. Plantation forests mostly consist of tree species that have been introduced and produce high value timber, with santol (*Sandoricum koetjape*) and mahogany (*Swietenia macrophylla*) being the most widely spread species. Plantation forests are not only areas planted artificially in rows, but they may have also been created by way of natural regeneration. The common criterion is the dominance of exotic species, especially high value timber species. Very often plantation areas are pieced together like a mosaic with seminatural forests and are not easily differentiated (UNIQUE, 2012).

According to UNIQUE (2012), there are around 500 hectares of plantation forest on Mahé. Plantation forests are also distributed on Praslin (51 hectares) and other islands (4 444 hectares) but due to either small quantity or high transportation costs, forest harvesting residues from these sources were not considered further (FAO, 2014a). Plantation forests on Mahé have MAI between 5-10 m^3/hectares (UNIQUE, 2012). Using average MAI of 7.5 m^3/hectares, annual increment for plantation forest on Mahé would amount to 3 750 m^3. The production of forest harvesting residues was estimated based on the assumption that plantations are being harvested at the level of annual increment so as not to reduce their growing stock. The calculation was done using the default values rate of felling removal and tree composition. The estimate of forest harvesting residues production from plantations forests on Mahé amounted to 1 073 m^3 per year (**Table 11**).

TABLE 11.

PRODUCTION OF FOREST HARVESTING RESIDUES

	HA	MAI (M^3/HA)	MAI (M^3/YEAR)	FOREST HARVESTING RESIDUES (M^3/YEAR)
PLANTATION FORESTS	500	7.5	3 750	1 073

Source: elaboration based on BEFS assessment results, 2020.

STEP 2: AVAILABILITY OF FOREST HARVESTING RESIDUES

Harvesting residues are usually left on the forest floor and are only occasionally used by local farmers for constructions. Thus, it is assumed that they are available for bioenergy production.

STEP 3: ACCESSIBILITY OF FOREST HARVESTING RESIDUES

The accessibility of forest harvesting residues mainly depends on the morphology of the terrain, in addition to the practicality of their collection, labour, and availability of machinery. First, the exact locations of plantations are required to estimate the accessibility of forest harvesting residues, however this information was not available. It is assumed that these residues would be more accessible than *Albizia* feedstock, as timber harvesting is already taking place at these locations. Nevertheless, the cost-effectiveness of their collection and utilisation for bioenergy should be analysed.

3.5.4 Biodegradable waste

STEP 1: PRODUCTION OF BIODEGRADABLE WASTE

Given that almost 60 percent of the waste is of an organic nature, major achievements could be made by introducing a source separation concept to divert waste from landfilling. By using this concept, organic waste would be separated and delivered to the existing municipal waste collection system. Once collected, the biodegradable waste should be processed by a suitable technology, such as composting or AD (COWI, 2019). Another option would be to collect mixed waste and implement mechanical biological treatment (MBT) that combines a sorting facility with a type of biological treatment. However, this would result in considerable losses of organic matter as well as represent a high contamination risk for AD. AD is particularly appropriate for organic waste with a high moisture content such as kitchen waste and food waste. As such, AD can be complementary to composting (aerobic processing), which is best suited for rough, structured wastes such as green waste from parks and gardens.

Around 70 000 tonnes of waste are delivered to the Providence landfill on Mahé annually. In addition, 10 500 and 1 100 tonnes are delivered to the landfills on Praslin and La Digue. Due to small quantities (L'Union) or lack of information on the waste composition (Amitié), only waste produced on Mahé and landfilled on the Providence landfill was further considered for bioenergy production.

STAR used 11 waste classes for their waste collection system on Mahé (**Table 3**). According to Krütli (Krütli *et al.*, 2018) waste class 3 (Green waste) is a possible option for feedstock mainly for AD, however, the quantity produced is rather small and more appropriate for composting. Waste class 5 (mixed waste) contains 5 percent kitchen waste, which does serve as AD substrate. However, separating that fraction from the rest of the waste necessitates a significant amount of labour and is therefore potentially very costly. The handling of kitchen oil is uncertain, thus Waste class 8 waste oil) was also excluded from the assessment. Class 9, 10 and 11 wastes are construction and demolition, inert, hazardous, and special waste and their organic content is negligible. Waste classes 1, 2, 4, and 7 include appropriate organic feedstock for AD and were further assessed for bioenergy production based on the information provided by Krütli (Krütli *et al.*, 2018).

Class 1 waste consists of MSW and commercial waste alike. More than half of this waste class contains organic material, mainly in the form

©Flickr/Trish Walker(Public Domain Mark 1.0) of kitchen waste, followed by green waste and cellulose packaging. Paper and cardboard can also serve as substrate in the AD process. However, they also significantly decrease the yield and were, as a result, excluded from potential feedstock for AD. Waste class 1 amounted to 26 867 tonnes per year in 2016; 18 percent of this waste was considered to be potential AD feedstock amounting to 4 836 tonnes per year (Krütli ***et al.***, 2018).

Class 2 waste contains a great deal of food waste from hotels, restaurants and other food producing and processing sources. These are valuable substrates for AD, especially because they can be delivered in large quantities and consequently the transport is more cost-effective. In 2016, 10 040 tonnes of this waste were delivered to the Providence landfill. It is considered that 25 percent (2 510 tonnes/year) of this waste would be suitable as potential feedstock for AD (Krütli ***et al.***, 2018).

Class 4 waste (liquid waste) amounted to 10 890 tonnes in 2016. The largest share of this waste was produced by IOT, which since then has finalised their wastewater treatment plant (WWTP) and concurrent AD, drastically reducing the availability of this waste. It is assumed that 52 percent of this waste would still be available as potential AD feedstock, comprised mostly of sludge from the PUC, WWTP, and waste from smaller fish producers. At the PUC WWTP sludge is pressed with a belt press, thus the dilution factor of 3.3 is used to estimate the total volume of sludge amounting to 28 314 tonnes of class 4 waste per year (Krütli ***et al.***, 2018).

Class 7 waste (Putrescent waste) is defined as "animal waste from abattoirs" and was included fully as AD feedstock (Krütli ***et al.***, 2018).

The total waste considered as a potential feedstock for AD and biogas production amounted to 36 743 tonnes per year (**Table 12**).

TABLE 12.

POTENTIAL AD FEEDSTOCK

WASTE CLASS	QUANTITY (TONNES/ YEAR)	SHARE CONSIDERED FOR AD	DILUTION	POTENTIAL AD FEEDSTOCK (TONNES/YEAR)
Class 1 (MSW + commercial)	26 867	18 percent (kitchen residues)		4 836
Class 2 (Commercial/ hotels)	10 040	25 percent (hotels kitchen residues)		2 510
Class 4 (Liquid)	10 890	52 percent	330 percent	28 314
Class 7 (Putrescent)	1 083	100 percent		1 083
Total	71 841			36 743

Source: Krütli ***et al.****, 2018.*

STEP 2: AVAILABILITY OF BIODEGRADABLE WASTE

A fraction of the waste suitable for AD produced on Mahé is currently landfilled at the Providence landfill and therefore not utilised in any way. Thus, the total quantity of this waste would be available for AD and biogas production.

STEP 3: ACCESSIBILITY OF BIODEGRADABLE WASTE

Biodegradable waste is already collected, albeit in mixed form, and is, therefore, accessible for bioenergy production. Source separation of organic waste would facilitate AD and enable higher biogas production. On the other hand, the higher cost of separated waste collection should be taken into consideration as well.

3.6 CONCLUSIONS

Based on the feedstock types identified, the biomass assessment analysis estimated the amount of feedstock produced and how much was potentially available for bioenergy production, as well as their geographical distribution in the Seychelles when possible. The assessment covered production and availability and listed the issues that would need to be addressed in terms of feedstock accessibility.

Following feedstock types were considered:

(i) Crop residues

This group considered residues spread in the field, collected in the field, and collected in the processing facility.

(ii) Livestock residues

This residue group included manure from pigs, chicken, and cattle.

(iii) Forest feedstock

Albizia forests and forest harvesting residues were considered within this feedstock group.

(iv) Biodegradable waste

This group considered the biodegradable portion of MSW and commercial waste, WWTP sludge and putrescent waste.

In terms of crop residues, due to the small agricultural production and small farm sizes in the Seychelles, only banana residues were deemed available for bioenergy production. The total quantity of banana residues, including false

trunk, leaves and peels, feasibly available for bioenergy amounts to 4 199 tonnes per year.

The commercial livestock sector in the Seychelles is dominated by some large producers that are already collecting animal manure either for sale or for utilisation on the agricultural land. The assessment of livestock residues shows that the total manure available for biogas production amounts to 7 430 tonnes per year. The highest amount of available manure comes from pigs (56.7 percent), followed by chicken manure (39.4 percent). Most of the manure (80.7 percent) is produced on Mahé.

The forest surface area and growing stock have been stable in the Seychelles, amounting to 40 666 hectares and 3.1 million m^3, respectively. Sustainable forest management in the Seychelles is important for the provision of ecosystem services, such as biodiversity conservation, amenity value, erosion and watershed protection, rather than timber production. Therefore, only the additional harvesting of ***Albizia*** forest at the level of a mean annual increment was considered for bioenergy production. The estimated potential on Mahé amounts to 20 000 m^3 per year. In addition to this, the potential of forest harvesting residues on plantations on Mahé was estimated at 1 073 m^3 per year.

Waste management poses a significant challenge to the Seychelles, due to a lack of funding and capacity, the high costs of transportation, the absence of engineered landfills and limited land area available for storage of waste. Around 70 000 tonnes of waste are delivered to the landfill on Mahé annually. In addition, 10 500 and 1 100 tonnes are delivered to the landfills on Praslin and La Digue. The total biodegradable waste available for biogas production on Mahé is estimated at 36 743 tonnes per year.

The main issue to focus on is the fact that collecting and mobilising these feedstocks can be expensive and challenging, and requires considerable logistics and coordination. The results, therefore, are to be interpreted as an initial indication of feedstock availability for energy production. Finally, the amounts of feedstocks that are actually accessible need to be realistically quantified.

CHAPTER

4

BIOENERGY AND FOOD SECURITY (BEFS) ASSESSMENT: BIOENERGY OPTIONS

The energy sector in the Seychelles is well developed, in fact, 96 percent of the country has access to electricity. Fossil fuel is the primary source of energy used in the Republic of Seychelles (97.5 percent) and the remaining portion is supplied with renewable energies. The main category of consumers of electrical energy in the Seychelles is the residential sector, accounting for over 32 percent of energy use. Industry is the second largest consumer of electricity with 36 percent total energy usage (Food and Agriculture Organization of the United Nations, 2013).

Nevertheless, the dependance on fossil fuels rather than local renewable energy sources represents a weak point in the islands' energy security. Despite the fact that the cost of petroleum has dropped from the high prices reached in 2014 – a period in which petroleum prices rose to more than 100 USD/barrel in smaller island states, such as the Seychelles, and fuel imports were around 30 percent of GDP (Weir, 2018).

Considering this context, the Second National Energy Policy (2010-2030) outlines the following objectives:

(i) enhance the internal energy supply;
(ii) decrease reliance on imported supplies;
(iii) focus on sustainable energy efficiency; and
(iv) increase diversification through the deployment of renewable energy sources, such as energy from waste.

More specifically, the Seychelles aims to reach 5 percent coverage of its electrical demand with renewable energy by 2020 and 15 percent coverage by 2030 (Goverment of Seychelles, 2010)

This transition towards a low carbon energy production is a field in need of development, together with contributions of different renewable energy options, such as the introduction of large scale RE plants, distributed generation, grid stabilizing technology such as battery and pump storage, the introduction of smart grid and smart meters (Seychelles Investement Board, 2021).

The "Seychelles Technology Needs Assessment Report – Mitigation," based on studies conducted on the island for energy generation from biomass options, concluded that a 5 MW capacity plant could be built using woody invasive species and energy crops. Moreover, based on the volume and characteristics of MSW generated on Mahé, a waste-to-energy plant would have a potential capacity of 7 MW. As a result, based on a barriers analysis and developing technology, waste heat recovery at the thermal power plant (for electricity generation), waste-to-energy, and utility-scale PV should be prioritized as RE power generation options (Government of Seychelles, 2016a).

The BEFS bioenergy technologies section analyses and compares the performance of different options to valorize the quantities of biomass resources, previously estimated as available for assessment within the specific Seychellois context. These are built on the techno-economic evaluation of different scenarios based on three potential marketable products: Compressed Biogas (CBG), electricity, and heat.

Thus, the five production scenarios described in the BEFS assessment present information about different processing capacities that can be supplied with potentially available biomass. On the economic side, details are provided on the unit production costs of each technology and the capital investment needs. Profitability indicators such as the BEFS' Profitability Zones Maps are presented using a set of defined comparison prices. Subsequently, and based on the different product output rates, the potential benefits for Seychellois consumers are explained. The combined techno-economic results and their impacts on consumers select the most feasible options and finally, analyse their potential role in the island's renewable energy and GHG saving reduction targets.

4.1 METHODOLOGY

The bioenergy options assessment covers wet and dry biomass for electricity, and heat and compressed natural gas production. Moreover, all of the options analyzed include a water desalination plant intended to self-supply all water consumed and prevent the depletion of natural water sources on the island. The following sections illustrate the technologies included within each of the assessment sub-components.

Water desalination

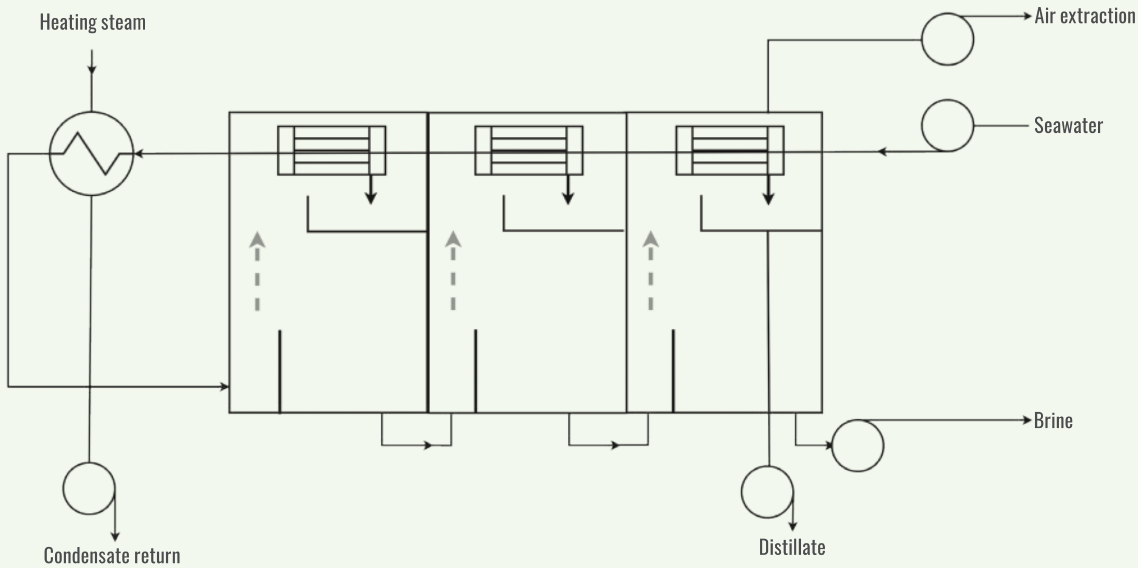
Desalination is a technology that allows for the removal of salt from water. The primary sources for desalination technologies include brackish water and seawater. Desalinated water is one of the primary water sources for those areas isolated from fresh water sources and it can be an alternative water source in industrial processes, commerce, and tourism that provides a continuous and reliable supply. However, the high production costs represent a significant constraint that currently makes this technology accessible only to those governments or industries whose have the funds to pay (Xie *et al.*, 2020; Almar water solutions, 2016; Belessiotis, Kalogirou and Delyannis, 2016). The two main desalination methods are thermal and reverse osmosis, but it is also possible to find combinations of both options, known as a hybrid (Son *et al.*, 2020).

Thermal desalination uses heat energy to separate salt from water in order to obtain purified water. This method is mainly featured by three technology options, namely multiple effect distillation (MED) multistage flash distillation (MSF) and vapor correction (VC):

- in multistage flash distillation (MFD) (see **Figure 16**), the high salinity water is forced to evaporate through a series of sudden pressure reductions in different chambers at operation temperatures ranging 90 – 110°C. A typical MSF plant might reach 30 chambers. In the end, freshwater is obtained when the last and final steam is condensed. Overall, this is a reliable and straightforward technology, however, it requires high capital investment and a high level of energy (Shatilla, 2020).

FIGURE 16.

MULTISTAGE FLASH DISTILLATION PROCESS



Source: Adapted from (World Bank, 2019).

- in the MED (see **Figure 17**), the high salinity water is passed through a series of evaporation-condensation cycles (usually 8-16 chambers) using progressively lower pressure at the different stages without adding extra heat. This procedure facilitates using a comparatively lower temperature (around 70°C), meaning lower energy requirements and capital costs, but higher operational complexity (Shatilla, 2020).
- During the vapour compression (VC) desalination process (see **Figure 18**), the evaporation of high salinity water is caused by the vapour compression rather than a direct heat change, as found in the other two methods. In turn, vapour compression can be produced by either using mechanical (electrically driven) or thermal (steam jet ejector driven). This technology is more suitable for small scale applications (Shatilla, 2020).

On the other hand, membrane-based methods allow for salt and water separation through the reverse osmosis (RO) process, where, opposite to the natural osmosis, mechanical energy in the form of pressure must be applied to induce the separation (Caldera, Bogdanov and Breyer, 2016.)

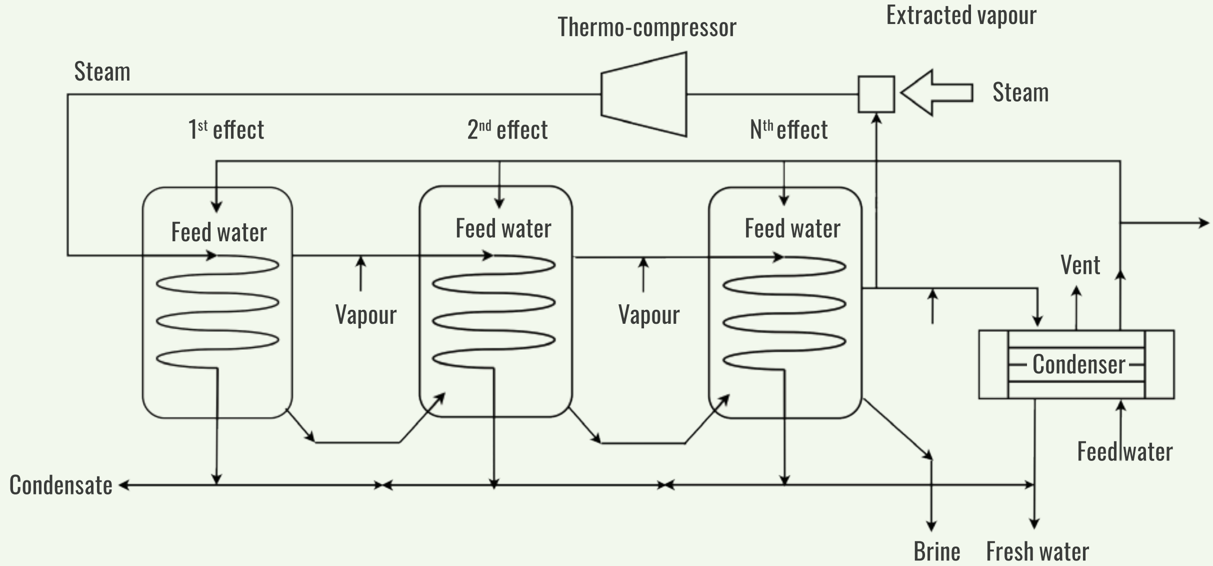
Initially, membranes were used to purify brackish waters due to their short life span. However, improvements on semipermeable membranes allowed for a better performance and life span, thus, membranes entered the water industry. Nowadays, this method, seawater reverse osmosis (SWRO), is used in more than 50 percent of the plants around the world, mainly to purify seawater (Belessiotis, Kalogirou and Delyannis, 2016).

In the case of desalination in the Seychelles, an important point to bear in mind is the seawater consumption of thermal and RO technologies.

It should be noted, the PUC Desalination Plant is located close to the Providence landfill and the sewage treatment plant. This desalination plant uses reverse osmosis technology to treat seawater, but it can even treat heavily polluted waters (Lai *et al.*, 2016)

FIGURE 17.

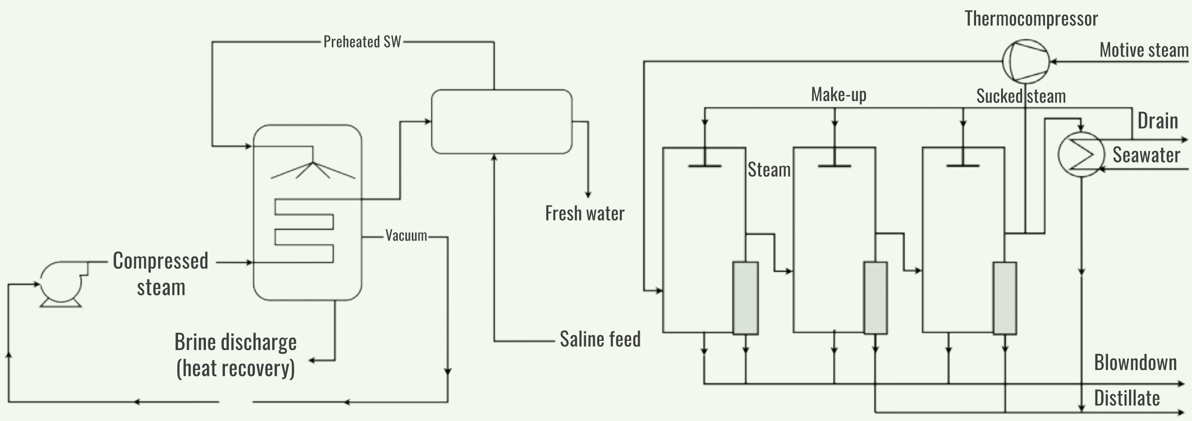
MULTIPLE EFFECT DISITILLATION (MED) PROCESS



Source: Adapted from (World Bank, 2019).

FIGURE 18.

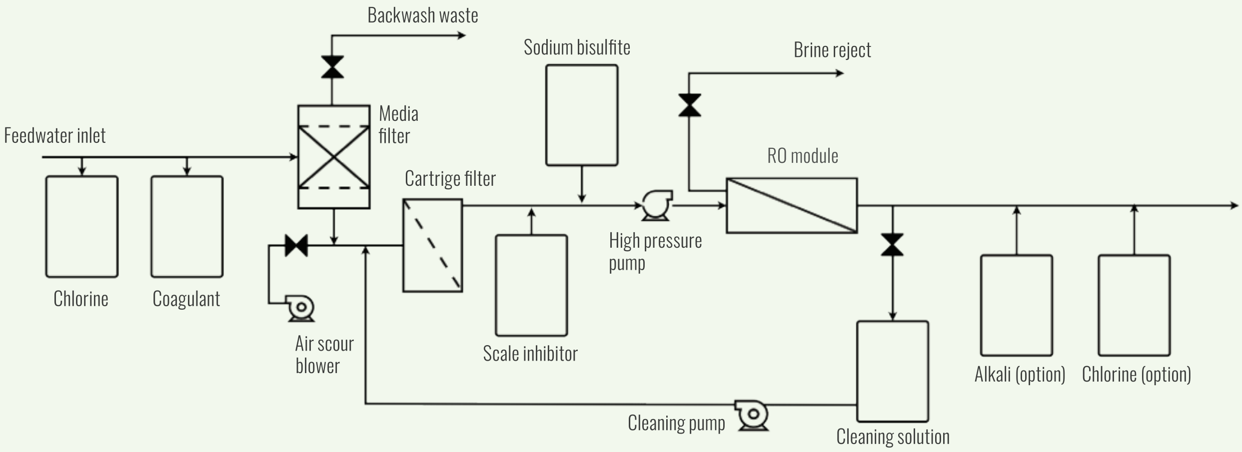
VAPOR COMPRESSION DESALINATION MECHANICAL (LEFT) AND THERMAL (RIGHT) PROCESSES



Source: Adapted from (Abdunnabi, belgasim and Ramadan, 2021).

FIGURE 19.

REVERSE OSMOSIS (RO) PROCESS



Source: Adapted from (World Bank, 2019).

Thermal processes consume comparatively more significant amounts of seawater with recovery ratios ranging from 10-20 percent, while the reverse osmosis option can reach 30-50 percent. Energy consumption is a critical feature in water desalination plants. Consequently, it is advisable to locate desalination plants close to energy plants, so that both can mutually benefit from the purified water of one and the energy generated by the other. In this sense, considering the demand for heat and electricity of desalination plants, cogeneration plants create a perfect situation for interacting with desalination plants (Advisian, 2019; Ghaffour, Missimer and Amy, 2013).

4.1.2 Biogas production and upgrading to CBG

Biogas is a clean, efficient, and renewable fuel produced from wastewaters, organic residues (e.g., manure discarded food), and other suitable biomass. This process is called AD and essentially comprises the biological decomposition of organic materials in an oxygen-free environment that yields a mixture of gases (mainly methane and carbon dioxide) and a by-product digestate useful as bio-fertilizer.

In particular, in this assessment for the Seychelles a large-scale industrial production will be taken into consideration. The biogas produced will be used for heat and electricity cogeneration or after upgrading and compression to obtain CBG, a suitable substitute for natural gas as fuel for vehicles.

Different technologies variations depend on feedstocks' properties, particularly the total solids (percent). The total solids content (TS) is the measure of suspended and dissolved solids in water and the feedstock availability in a stream to be converted into biogas. Consequently, a feedstock with high TS content will require a smaller digestor than a feedstock with low total solids. Moreover, if a feedstock has solid content that is too high, the digestion operation will be complex and total solids must therefore be reduced. These feedstocks will need to be mixed with water or low-solid waste, e.g., wastewater treatment sludge, to dilute the solid's content to the operating range (Yang *et al.*, 2015). Therefore, the AD operation is broadly classified into two different categories, according to the TS content: i) low solid content (LS), also called liquid AD, containing between 15 to 20 percent TS; and ii) high solid (HS) or solid-state AD, with a range of between 22 to 40 percent of TS (Monnet, 2003).

The core of biogas production is the digestor. Up-flow anaerobic sludge blanket reactors (UASB) are better suited to treating feedstock with low total solids content (<15 percent), e.g., soluble industrial wastewater, municipal sewage, sewage sludge, aquatic/marine plants,

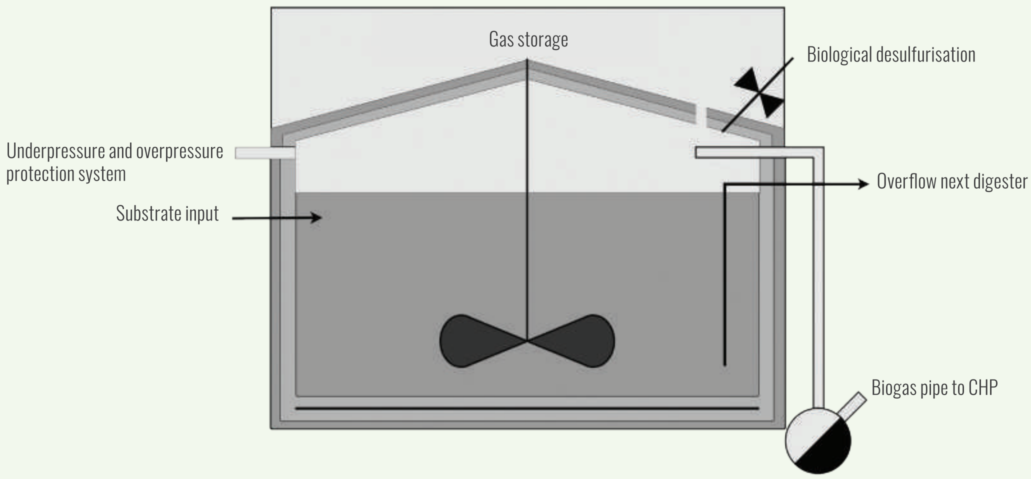
particulate industrial wastes, and animal manures, will perform better in anaerobic filter and fluidized bed reactors. On the other hand, batch reactors treat options with high total solids content (>15 percent), e.g., municipal solid waste, agricultural residues, energy crops. Finally, the continuous stirred tank reactor (CSTR) can treat feedstock or a feedstock mixture using many options.

In this study and considering the nature of feedstock options that comprise wastewater sludges, crop and livestock residues, a CSTR option was selected.

The CSTR (see **Figure 20**) is the most common and easy-to-use biodigester for treating feedstock with high solid concentration, and chemical oxygen demand (COD) values higher than 30 000 mg/L (Chan ***et al.***, 2009; Wang ***et al.***, 2005). Usually, the CSTR volumes range between 500 m^3 and 700 m^3, with an organic loading rate (OLR) ranging from 1-4 kg dry organic matter per m^3 per day(Wang ***et al.***, 2005). The CSTR digester is mainly used to stabilize the sludge by converting the biodegradable fractions into biogas(Massoud, George and Robert, 2007). It is generally operated at high temperatures in order to increase the process rates. CSTR digestion units are designed in large volumes that make perfect mixing difficult. Mixing is done mechanically or by recycling either flow or the produced biogas. Therefore, the efficiency of mixing is essential to modeling the solids transport in the reactor and evaluating the Solids Retention Time (SRT). Materials with very high COD loading rates (30 kg per m^3 per day) can be digested using this technology, reaching an adequate treatment at lower (Hydraulic Retention Times) HRTs (even 4 hours) (Wang ***et al.***, 2005). Overall, the removal efficiency of 85-95 percent of the COD of the inlet material, and methane content of 80-95 percent in the biogas produced, have been reported for this type of digestion (Chan ***et al.***, 2009; Wang ***et al.***, 2005).

FIGURE 20.

CSTR DIAGRAM



Source: Adapted from (Hofmann, 2020).

Biogas produced from AD mainly contains methane (50–70 percent) and carbon dioxide (30–50 percent) plus other gases such as N_2, OS, H_2S, and NH_3. These gases should be removed to increase the calorific value of the output gas. Additionally, H_2S and NH_3 might have harmful effects on valves, tubes, and motor engines. The biogas valorization comprises a series of stages intended to remove undesired gases from raw biogas, aiming to obtain a gas that fits the technical specifications required for its final use (i.e., cooking fuel, boiler fuel, injection to the natural gas grid, transport fuel, chemicals production). For biogas usage as CBG in engines is customary to remove H2S, CO_2, and water (Angelidaki ***et al.***, 2019). At least three major steps are included in the biogas valorization process (see **Figure 21**).

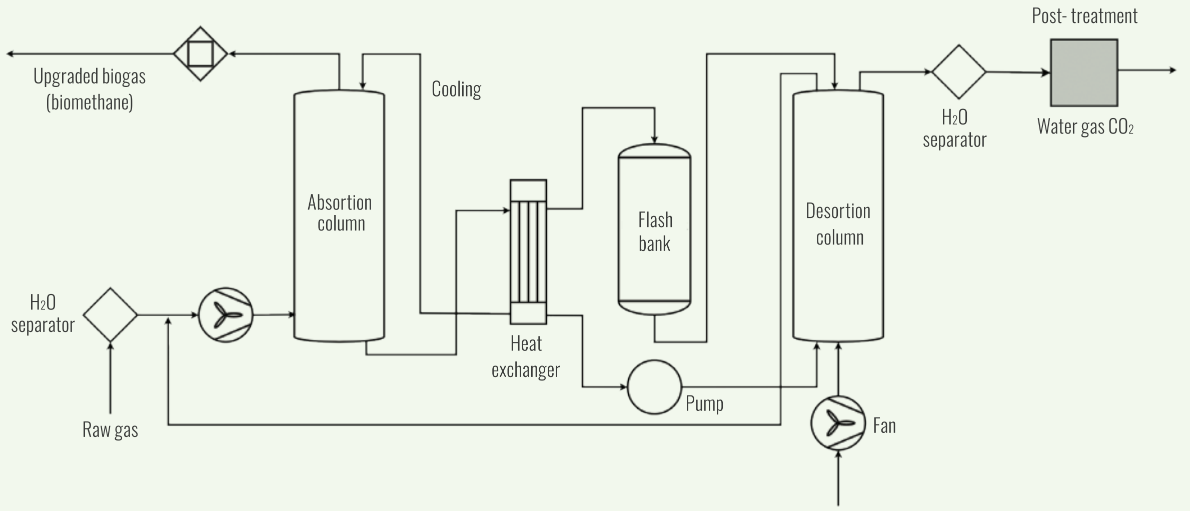
1. Desulfurization: this step is dedicated to removing H2S from raw biogas. Even the most straightforward biogas application for home fuel cooking requires this step. At the industrial level different options exist such as in situ chemical precipitation, adsorption, absorption, and membrane separation (Angelidaki ***et al.***, 2019).
2. Upgrading: this stage is intended to remove carbon dioxide from raw biogas. Different technologies for biogas upgrading have been developed, which are the most widespread and mature; these are based on the physicochemical removal of CO_2. These physicochemical methods include physical absorption (water scrubbing, organic solvent scrubbing), chemical absorption, adsorption, cryogenic separation, pressure swing adsorption (PSA), membrane technology, and chemical hydrogenation(Angelidaki ***et al.***, 2019). For this assessment, it was decided to use water scrubbing, considering the water availability from the desalination plant. The water scrubbing process is mainly used for CO_2 removal, although it can also remove H2S. The water scrubbing process is based on the higher solubility of H2S and CO_2 in water compared to CH_4. For instance, CO_2 has 26 times higher solubility in water as compared to methane at 25 °C (Khan ***et al.***, 2021). Water scrubbing is carried out in a packed column, allowing a more efficient gas-liquid mass transfer. A countercurrent regime is preferred, where the compressed gas at 6–10 bar the bottom is passed from bottom to tops and pressurized

water from the top to the bottom. Usually, water scrubbing can reach a CH_4 purity of 80–99 percent, depending on the volume of non-condensable gases (i.e., N_2 and O_2), which cannot be separated from CH_4. There are also CH_4 losses due to dissolution in water, ranging from 3 to 5 percent (Charcosset, 2014). Water scrubbing also allows for the simultaneous removal of oil and dust particles during the absorption of water. However, operating and investment costs can be high due to the energy-intensive solvent regeneration and its moderate to high operating pressures.

3 Finally, the obtained stream is rich in CH4 80–90 percent. It is compressed at high pressure (200 bar) to obtain compressed biomethane gas (CBG) is stored in CBG cascades. From there, CBG is ready to supply vehicles (Gustafsson *et al.*, 2020).

FIGURE 21.

BIOGAS UPGRADING TO BIOMETHANE



Adapted from (Awe ***et al.****, 2017).*

4.1.3 Cogeneration of heat and power

Cogeneration systems are thermodynamically efficient options to simultaneously produce heat and electricity as mechanical and thermal energies. For this reason, cogeneration systems are also named CHP. This setup satisfies both energy requirements of the targeted system. Moreover, the surplus electricity produced can be sold to the public electricity grid.

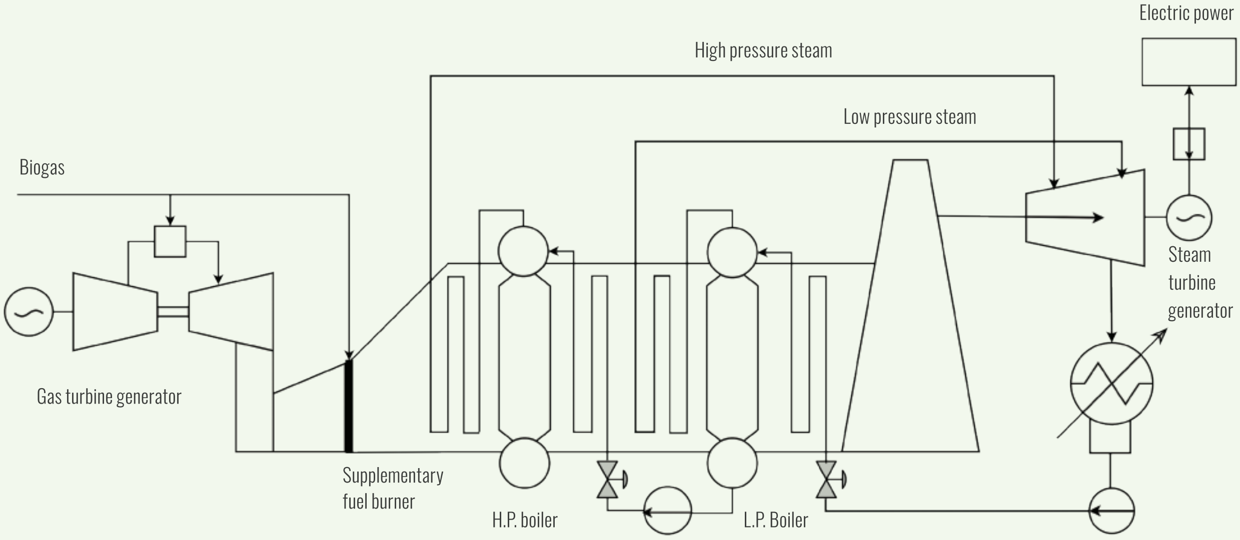
CHP systems can produce energy options using a single fuel option, such as oil, coal, natural gas, or biomass. It provides high cost and energy savings and greater operating efficiencies than systems designed to produce heat and power separately.

Overall, the main advantage offered by CHP systems is lesser fuel consumption to produce the same amount of energy, compared to separate heat and power production systems (Quintero and Cardona, 2011; Rincón *et al.*, 2014; Rincón, Moncada and Cardona, 2013).

Steam is a key element in the cogeneration system, primarily used as a means for transporting energy. Steam has several advantages over other energy carriers, such as low toxicity, ease of transportability, high efficiency, high heat capacity and relatively low costs. Steam holds a significant amount of energy on a unit mass basis, which can be extracted as mechanical work through a turbine or as heat for process use (see **Figure 22**). Since the heat content of steam is stored as latent heat, large quantities of heat can be transferred efficiently at a constant temperature, which is a useful attribute in many process-heating applications (Prasad, 1995; Sanjay, Singh and Prasad, 2009; Zheng and Furimsky, 2003).

FIGURE 22.

COGENERATION OF HEAT AND POWER PROCESS



Source: Authors.

Considering the options used as fuel in this study – mostly biomass residues – biomass-fired cogeneration systems were considered. This technology first comprises separated biomass combustion to use a combination of gas turbines and heat steam recovery generator (HRSG) to generate electricity and heat as steam at single, double, or even triple pressure levels (Uddin and Barreto 2007). Depending on the needs of the targeted system, all the electricity and heat cogenerated can be directly used. Alternatively, all steam can be further passed through a series of back-pressure steam turbines to generate additional electricity. This setup dramatically increases the overall electricity output, but in turn, increases the capital investment too.

4.2 FEEDSTOCK CHARACTERISTICS

This section describes the main features related to the definition of feedstock collection costs, feedstock properties, and their final use for energy production.

4.2.1 Availability and classification

The feedstock availability refers to the physical quantities available per year. The natural resource assessment identified the quantities potentially available for the list of banana and livestock residues, woody feedstock, and biodegradable waste (Class 1, 2, 4, and 7). These feedstocks were also identified as suitable for energy production and therefore, can be appropriately converted to energy, while logistical issues (e.g., transport, collection, and storage) can be realistically solved. A summary of the quantities identified as available is presented in **Table 13**.

TABLE 13.

SUMMARY OF QUANTITIES AVAILABLE FOR ENERGY PRODUCTION

FEEDSTOCK TYPE			AMOUNT	UNIT
CROP RESIDUES	BANANA	PSEUDOSTEM	3 346	TONNES/YR
		LEAVES	357	TONNES/YR
		PEELS	496	TONNES/YR
LIVESTOCK RESIDUES	PIGS	MANURE	1 495	TONNES/YR
	LAYERS	MANURE	993	TONNES/YR
	BROILERS	MANURE	1 932	TONNES/YR
	CATTLE	MANURE	310	M3/YR
WOOD FEEDSTOCK	FOREST RESIDUES FROM PLANTATIONS		716-1 431	TONNES/YR
BIODEGRADABLE WASTE	CLASS 1 MSW + COMMERCIAL		4 836	TONNES/YR
	CLASS 2 COMMERCIAL/HOTELS		2 510	TONNES/YR
	CLASS 4 LIQUID		28 314	TONNES/YR
	CLASS 7 PUTRESCENT		1 083	TONNES/YR

Source: own elaboration BEFS assessment.

Overall, the technologies for energy production selected in this study for the Seychelles are based on the use of two possible feedstock categories: wet residues and dry residues. This classification is made according to their water content. High water content residues feature wet residues. The water will reduce the combustion efficiency if these were directly burned, and their drying might be uneconomical. Otherwise, dry residues have low water content and might be efficiently combusted. Hence, livestock residues, banana residues, Class 1 organic fraction MSW, Class 2 industrial and commercial waste, Class 4 liquid waste-PUC sewage sludge, Class 7 putrescent waste were considered as wet residues, are therefore more suitable for anaerobic co-digestion in biogas production, where they will be mixed with additional water. Class 3 green waste will be considered as a dry residue and directly combusted in CHP systems.

4.2.2 Plant capacities

Plant capacities are based on the technologies and targeted energy products selected for the Seychelles in this assessment. It is feasible to build different scales of energy plants, which in reality will depend on how much available feedstock can potentially be collected and mobilized across the island. In order to describe the process in this assessment, four stereotypical plant capacities were analyzed and compared. The units used for each capacity vary according to the end energy product as follows: CBG units are m^3 methane/day; electricity units are kWe (kilowatts of electricity); and finally, heat units are kWth (kilowatts of thermal energy) as appears in **Table 14**.

TABLE 14.

PLANT CAPACITY EQUIVALENCES FOR DIFFERENT ENERGY OUTPUTS FROM WET RESIDUES

	SIZE 1	SIZE 2	SIZE 3	SIZE 4	
BASELINE	399 900	138 000	4 080 000	5 799 900	m3 Biogas/year
SCENARIO 1	800	2 800	8 200	11 600	m3 Methane/day
SCENARIO 2	80	277	819	1 164	kWte
SCENARIO 3	44	151	448	637	kWte
	66	227	673	957	kWth

4.2.3 Feedstock properties

The primary feedstock property is the energy potential. This potential can either be released directly in dry residues or after conversion to biogas in the case of wet residues. As for the energy content of dry residues options, each type will have its own chemical composition in terms of carbon, hydrogen, oxygen, nitrogen, and sulfur. The relative quantities of these elements will determine the total potential energy contained in a feedstock. In addition, parameters such as moisture, fixed carbon, and volatile carbon will determine how easy it will be to release this potential. The calorific value of a feedstock measures the combination of all these parameters, or its equivalent property, lower heating value (LHV).

Regarding the energy potential for wet residues, the main indicator was the realistic methane potential (RMP). The RMP measures the potential of a feedstock to produce biogas, considering its actual production conditions such as hydraulic retention time (HRT), total volatile solids (S0), ultimate methane yield (B0), the maximum specific growth rate of microorganisms (µm), and the kinetic factor (K). The combination of all of these elements was taken into applied in Hashimoto's equation (Equation 1), and is a good indicator of the realistic production rates of methane in a specific feedstock under a given set of conditions (Hashimoto, Varel and Chen, 1981). Similar to the LHV, the RMP has a remarkable effect on the energy potential of biogas and the energy produced from it. Therefore, feedstock with a higher potential to generate biogas should be the preferable option.

EQUATION 1

$$RMP = B_O . S_O * \left(1 - \frac{K}{HRT.\ \mu_M - 1 + K}\right)$$

Given the high number and relatively low available volumes of wet residues for biogas production, it was decided to combine them in a single factory. This production strategy is called codigestion, however, this mixture should not be completely arbitrary. In order to understand at what ratio different feedstock can be mixed in codigestion systems, one rule of thumb is to consider the C:N ratio of components being taken into account. During AD, the different chemical components of feedstock (i.e., C, H, N, O) are used selectively by different digestion bacteria, where the specific ratios of organic matter (carbon) to nitrogen are essential for optimal digestion and avoid inhibitory effects. In this sense, C:N ratios higher than 23:1 are likely to be unsuitable for optimal digestion, while rates below 10:1 might inhibit the digestion process (Marchaim, 1992). A summary of suitable feedstock options for codigestion in biogas production is presented in (see **Table 15**).

TABLE 15.

PHYSICO-CHEMICAL PROPERTIES FOR FEEDSTOCKS

		VOLATILE SOLIDS (VS PERCENT)	BIOMETHANE POTENTIAL (BMP)	METHANE CONTENT (CH4PERCENT)	TOTAL SOLIDS (TS PERCENT)
	RESIDUE	kg volatile solids/kg total solids	m3 CH4/tonnes VS	m3 CH4/m3 biogas	Total solids/total fresh matter
BIODEGRADABLE WASTE AND WASTEWATERS	Class 1 - MSW + commercial	97 percent	303.00	65 percent	28.0 percent
	Class 2 - Industrial and commercial	34 percent	610.00	61 percent	35.8 percent
	Class 4 - Liquid	4 percent	525.00	60 percent	5.3 percent
	Class 7 - Putrescent (fish)	28 percent	435.00	69 percent	31.4 percent
LIVESTOCK RESIDUES	Pigs manure	58 percent	356.00	60 percent	30.8 percent
	Layers manure	60 percent	127.00	60 percent	25.9 percent
	Broilers manure	60 percent	127.00	60 percent	25.9 percent
	Cattle manure	85 percent	153.00	60 percent	15.0 percent
CROP RESIDUES	Banana residues mixture	91 percent	292.00	60 percent	25.0 percent

Source: compiled from values reported by (Bougrier, Delgenès and Carrère, 2006; Bundhoo, Mauthoor and Mohee, 2016; El-Mashad and Zhang, 2010; Navickas ***et al.****, 2013; Nges, Mbatia and Björnsson, 2012; Zhang, Lee and Jahng, 2011).*

4.2.4 Feedstock costs

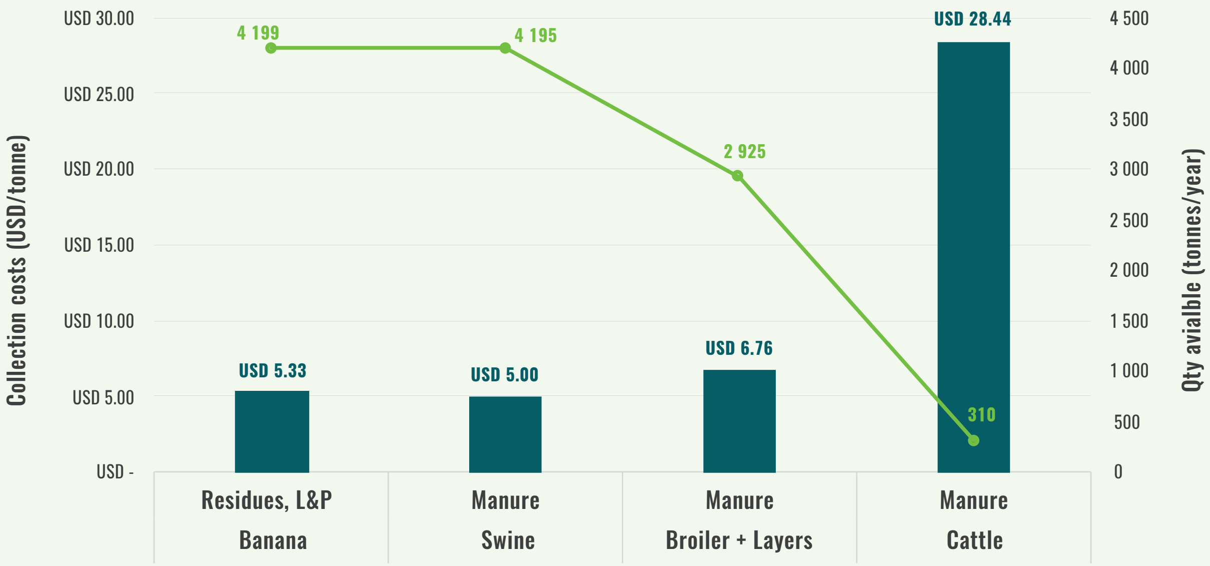
All feedstock considered independently in this assessment are wastes; these resources must be collected from their sources and transported to the energy plant. Banana residues can be collected during harvesting and processing. Livestock residues (i.e., swine and cattle manure as well as broilers and layers) can be collected directly from their farms. Hence, in this case, it was assumed that there would be no in-farm collecting costs. Finally, for waste classes 1, 2, and 7, the official STAR company fee will be paid for their collection.

Once residues are collected, they need to be transported to the bioenergy processing plant. The transport cost depends on the distance as well as unitary costs. First, this parameter will be affected by the current feedstock uses, which will determine the collection distance. In other words, for the feedstock with a large number of competitive uses, bioenergy producers will need to travel even further and visit more collection sites in order to obtain the feedstock required. Moreover, transport costs will depend on the condition of the roads in the country, fuel prices, type of vehicle and the salaries of the personnel hired to drive the vehicle and load and unload the charges.

Nevertheless, class 4 waste (liquid - sewage sludge) is the most abundant residue, but as the primary codigestion feedstock, the bioenergy plant will be located as close as possible to its source to guarantee supply and reduce costs. The obtained collection costs are presented in **Figure 23** and **Figure 24**.

FIGURE 23.

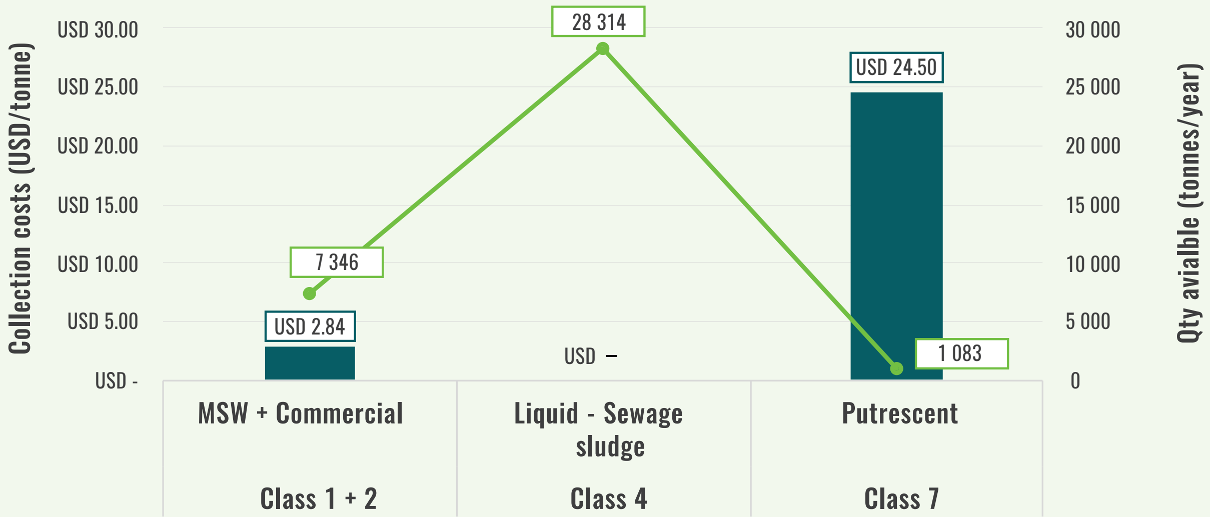
COLLECTION COSTS FOR BANANA AND LIVESTOCK RESIDUES



Source: own elaboration BEFS assessment.

FIGURE 24.

COLLECTION COSTS FOR WASTES CLASS 1,2,4 AND 7



Source: own elaboration BEFS assessment.

4.2.5 Data collection

The data used for these components of the BEFS assessment were collected from local sources such as the Ministry of Environment and local consultants (BEFS Seychelles Survey, 2019). Other technical parameters, efficiencies, and biomass properties were obtained from a literature review and will be directly cited throughout the report. The details of the data and the respective values are shown in **Table 16**.

TABLE 16.

MAIN DATA USED IN THE ASSESSMENT

	ITEM	VALUE	UNIT
	WATER	2.02	USD/m3
FUEL PRICES	NaOH	310.00	USD/t
	Skilled worker	0.46	USD/h
	Unskilled worker	0.26	USD/h
	Diesel price	0.82	USD/l
	Electrcity selling price	0.15	USD/kWh
	Heat cost	16.81	USD/t steam
	Natural gas	0.06	USD/m3
	Gasoline price	0.99	USD/l gasoline
	Fuel Oil - FOB	1.62	USD/gallon
		0.36	USD/l
	SEYPEC Margin	17	percent
	Fuel oil cost	0.42	USD/l
	Sugar price	1.10	USD/kg
ENERGY DEMAND	Electricity demand per hh	4 094	kWh/yr/hh
	LHV Bio CBG	36.6	MJ/m3
	LHV gasoline	43.4	MJ/l
GENERAL DATA	Household size	3.8	Person/hh
	Working hours per day collection	8	
	Operating days per year	300	
	Maintenance - Thermal	20	percent
	Maintenance - Osmosis	40	percent
	Electricity consumption per household		
ECONOMIC	Discount rate	10	percent
	Interest rate	7	percent

Source: Data collected from (Alemseged, 11AD; BEFS Seychelles Survey, 2019; Edwards et al.*, 2014; IPCC, 2006; Lai* et al.*, 2016; NationMaster, undated; Quijera, Alriols and Labidi, 2014; SEC, 2017; Seypec, 2021; United Nations, 2017).*

4.2.6 Financial viability

Financial viability is a decision-making supporting tool for future investors. It can help determine how financially attractive potential investments are. MJ/l kWh/yr/hh The financial viability was calculated using three sequential steps:

4.2.7 Calculation of production costs

The production costing was carried out as a tool to measure how much each energy unit produced in the bioenergy factory costs. Overall, the costs can be classified as fixed costs, that is, those costs that are independent of the production quantities (e.g., labour costs, storage costs); variable costs, such as costs that vary with the production quantities (e.g., main feedstock costs, other raw material costs, utility costs); and operating expenses (i.e., annual depreciation, maintenance, plant overhead, and general and administrative costs). The allocation system used in the calculation of production costs was the traditional method. The share of each individual cost was determined by identifying the largest contributors, thus, it was possible to evaluate potential measures to reduce production costs.

4.2.8 Calculation of cash flows

The free cash flows were used for calculating the financial flows going in and coming out of the project over a fixed time period. In the assessment, the time horizon was fixed at 20 years for all technologies except for charcoal production. All of the calculations were considered as real cash flows due to the fact that the influence of inflation rates was excluded. Revenues, production costs, and operating expenses were taken into consideration for free cash flow calculations.

Revenues were calculated from the potential sales of each energy product at their potential market prices. They were also used as part of the analysis to build scenarios to calculate the profitability of the different energy end-use options under different market conditions. Further explanations and the specific prices will be presented in each section.

4.2.9 Calculation of profitability

The figure of merit that is used in the BEFS assessment to estimate the economic value of an investment was the Net Present Value (NPV). The NPV equation presents the cumulative value (revenues – expenses) adjusted to the reference time, where the term $(1+i)^n$ is the discount factor and is called the discount rate (El-Halwagi, 2012)working, and total; for example, the discount rate collected for the Seychelles was 10 percent (BEFS Seychelles Survey, 2019). This value falls within the standard for bioenergy projects developed in Africa, ranging from 9 to 11 percent(Buchholz ***et al.***, 2013; Walekhwa, Lars and Mugisha, 2014; Wicke ***et al.***, 2011) environmental and economic reasons. We analyzed an economic model of a vertically integrated system of short-rotation woody crops (SRWC. In sum, the acceptance criterion for a bioenergy investment is that the NPV is greater than zero.

EQUATION 2

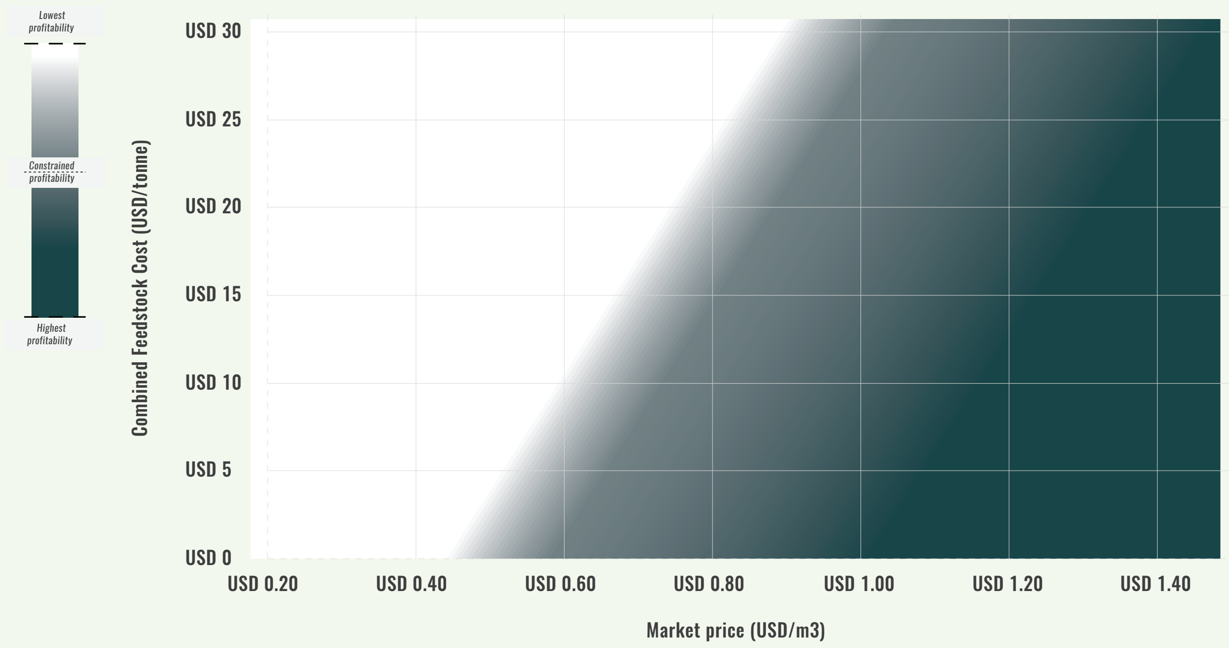
$$NPV = \sum_{i=o}^{n} \frac{Annual\ cash\ flows}{(1+i)^n}$$

4.2.10 Market profitability zones maps

The results of production costs, financial viability and investment requirements were used to define which technology scenarios would be financially viable. Furthermore, the combined analysis of all of the elements as previously mentioned was based on the Profitability Zone Map (PZM) (Rincon ***et al.***, 2019), but modified to account for variations in the main product's market price. These maps are called market profitability zones maps (MPZM). In these profitability maps, feedstock are positioned according to their costs and the market price of their derivative products are plotted on an X-Y chart (see **Figure 36**). These maps are based on a specific comparison price scenario and specific technology and production conditions.

FIGURE 25.

MARKET PROFITABILITY ZONES MAP EXAMPLE



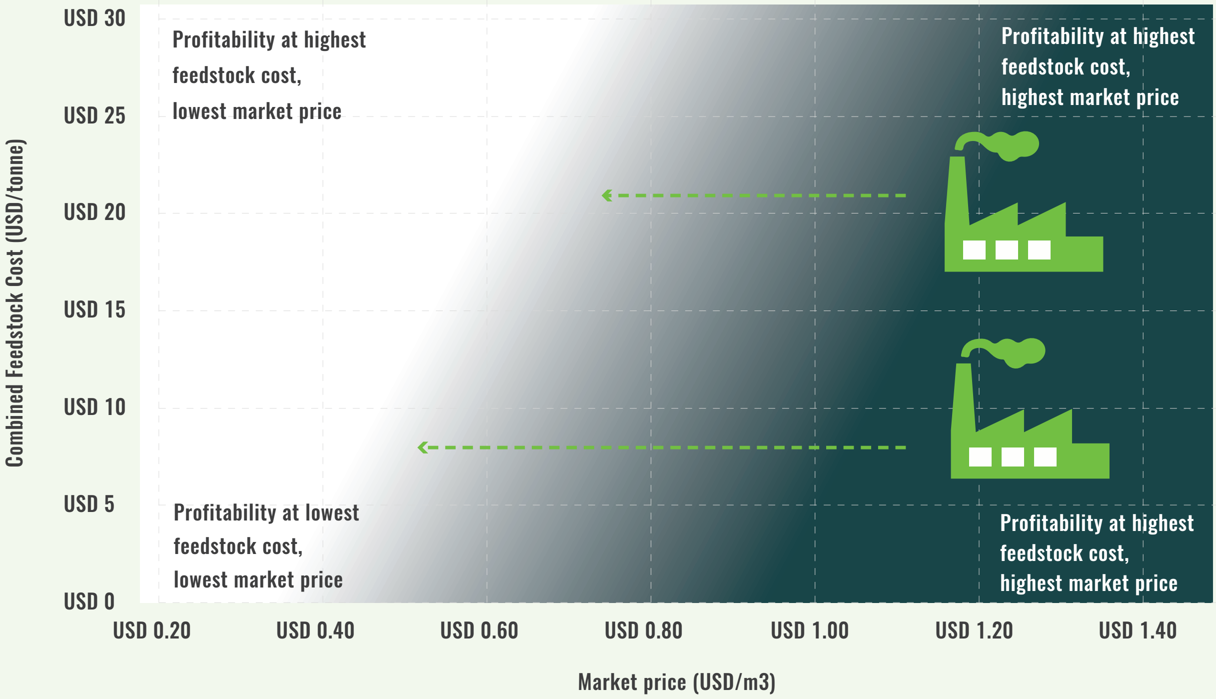
Source: own elaboration BEFS assessment.

The MPZM are comprised of three zones marked by different colors and defined according to the maximum feedstock costs identified for product market price (see **Figure 26**). The darkest blue includes feedstock costs and products sold at an acceptable price to fulfill the profitable production criteria for all technology options and plant sizes. The white zone contains feedstock that does not meet profitability requirements because of their high feedstock cost or low market price of their products. A gradient scale of dark blue will represent all situations in between to white. Finally, the MPZM will present the NPV value obtained at each of its four corners, showing combinations of minimum/maximum feedstock costs and minimum/maximum market prices.

Overall, the MPZM are also helpful in identifying the maximum price for any given feedstock under a set of production conditions. For example, a bioenergy project with a product sold at 1.2 USD/m^{3}potential and feedstock cost of 5 USD/tonne could still be profitable if the market price were reduced by 0.45 USD/m^3. Conversely, a product sold at the same price but with a feedstock cost of 15 USD/tonne, would tolerate a maximum reduction of up to 0.7 USD/m^3 (see **Figure 37**. Moreover, these maps can help provide a comparison of various feedstock options where products might have comparable market prices but different feedstock costs. As a result, this will make it easier to understand which option would be more profitable as well as stable in terms of production.

FIGURE 26.

EFFECT OF MARKER PRICES VARIATIONS IN MPZMS



Source: own elaboration BEFS assessment.

4.3 RESULTS

4.3.1 Seawater desalination plants

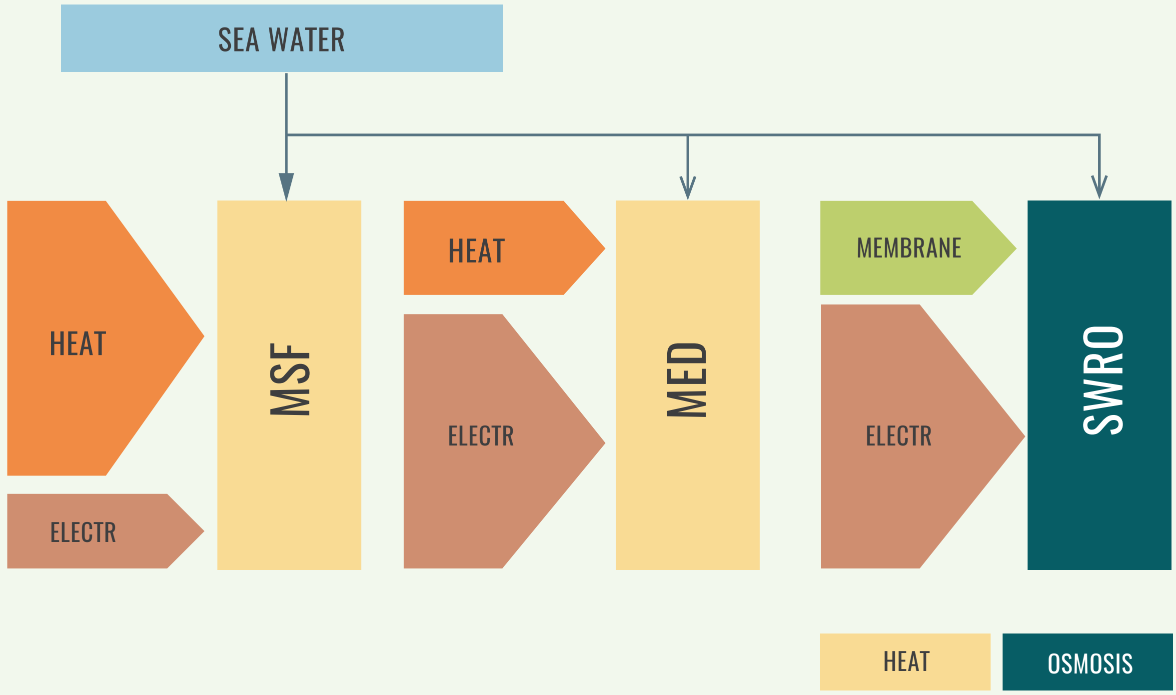
In order to avoid the adverse impacts of the lack of water on the island, the bioenergy production project must obtain its water supply. To this end, the possibility of using seawater desalination technologies was analysed, and is considered to be the safest option to supply water for the project, while safeguarding the natural sources of freshwater for human consumption. The techno-economic assessment was performed with a sample size of 0.35 MLD water, which was enough to supply a 1 MWel factory. The three technology options considered were two thermal-based (MSF and MED) and one reverse osmosis based seawater reverse osmosis (SWRO) (see **Figure 27**).

Figure 28 supervises the annual production costs in terms of US dollars per year. It was found that for this specific size MED technology has the lowest cost, while SWRO technology has the highest cost.

Thermal desalination technologies (MSF and MED) use large amounts of heat energy to separate distilled water from high salinity water. On the other hand, osmosis technologies (SWRO) use high-pressure pumps to overcome the osmotic pressure of the seawater requiring large amounts of electricity, but no heat (Almar water solutions, 2016). When the share of the annual production cost was analysed, in the case of thermal technology it was found that the highest contributors were heat (20-36 percent) and electricity (26-52 percent) as expected, while the reverse was true in the case of osmosis, which was electricity (55 percent) only (see **Figure 29**).

FIGURE 27.

WATER DESALINATION TECHNOLOGIES USED IN BEFS ASSESSMENT

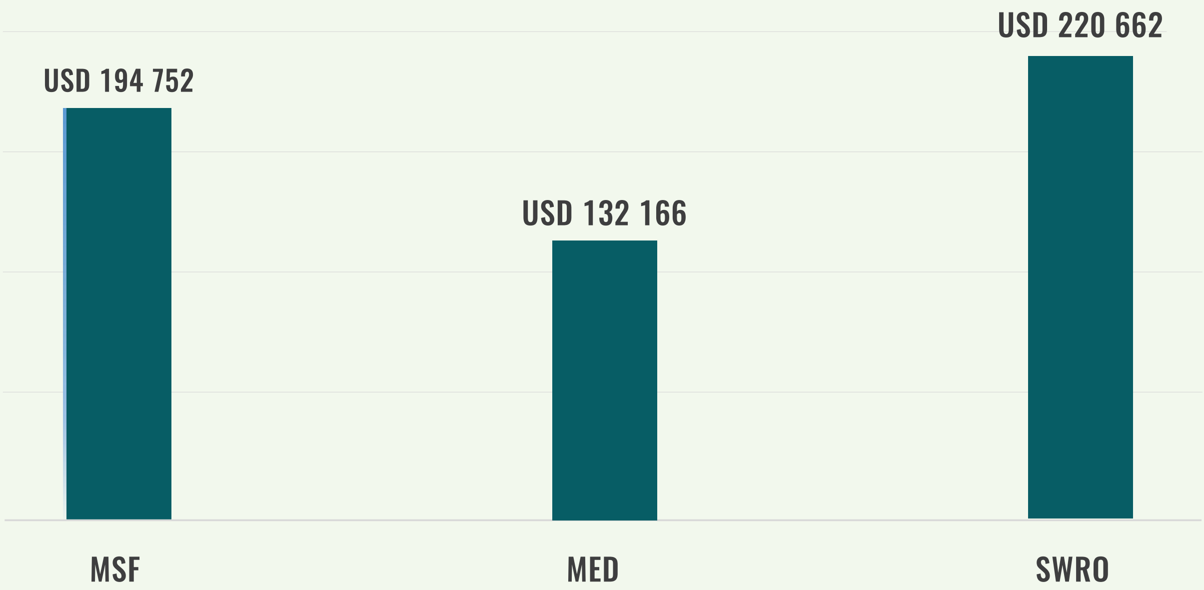


*MSF : Multistage flash distillation, MED: Multi-effect flash distillation, SWRO: Sea water reverse osmosis

Source:authors.

FIGURE 28.

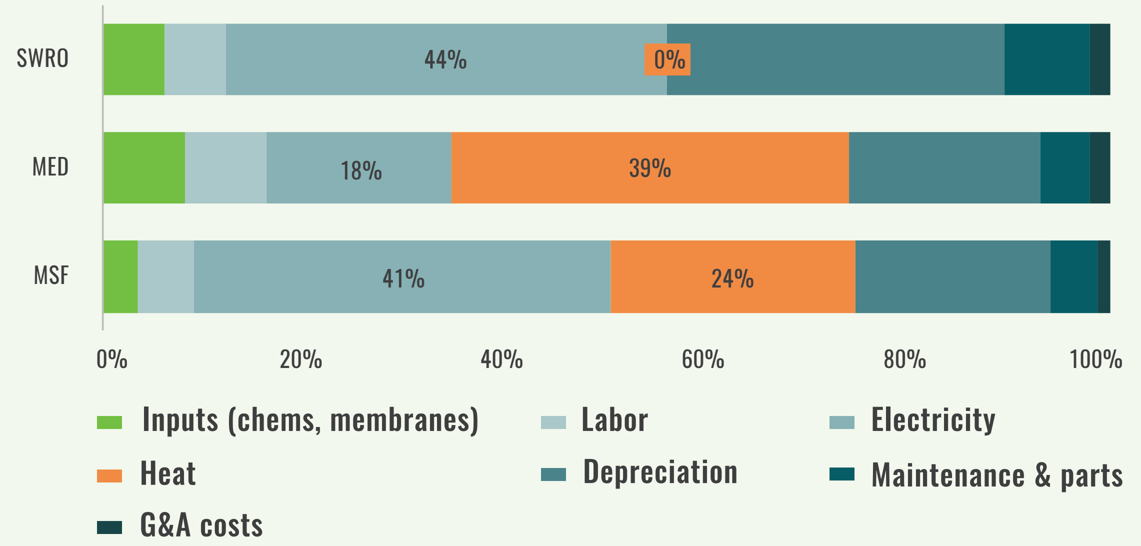
ANNUAL PRODUCTION COST FOR SEA WATER DESALINATION PLANTS (USD/YEAR)



Source: authors.

FIGURE 29.

SHARE OF PRODUCTION COST FOR SEA WATER DESALINATION TECHNOLOGIES

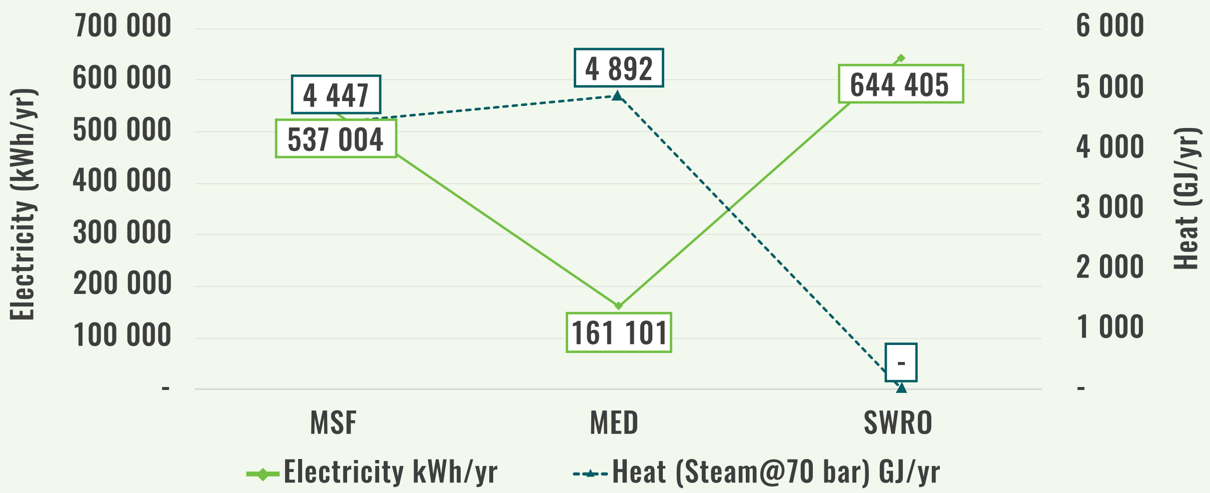


Source: authors.

A close look at the energy consumption of different technologies for the same plant capacity (0.35 million liters per day-MLD) revealed that the annual combined heat and electricity expenditure of thermal technologies is critical to their design (see **Figure 30**). Therefore, the energy provision for these alternatives is a critical factor in their design. That is why desalination literature suggests that this kind of plant should be located to energy plants (Elsaid *et al.*, 2020; Son *et al.*, 2020).

FIGURE 30.

ENERGY CONSUMPTION AS HEAT AND ELECTRICITY FOR SEA WATER DESALINATION TECHNOLOGIES

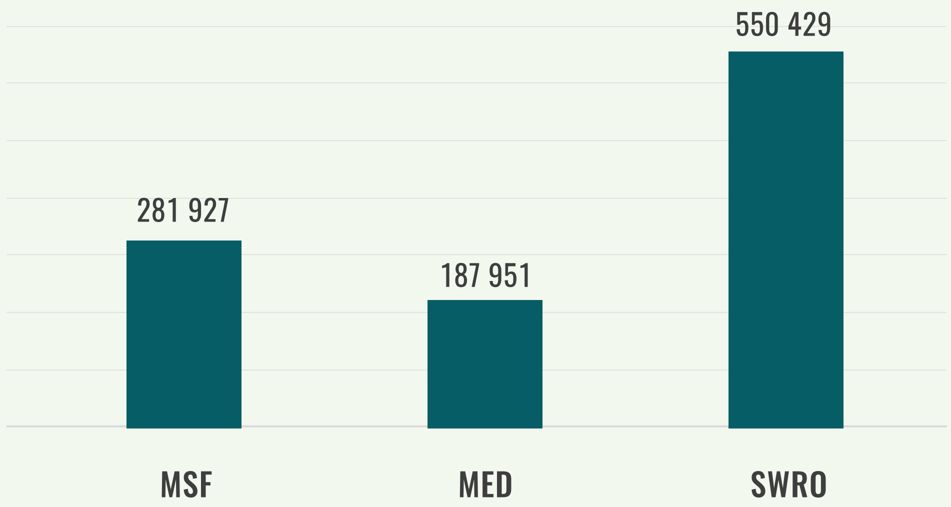


Source: authors.

Globally, the predominant type of desalination technology used is SWRO. However, there is a trade-off between the operative and capital investment costs, due to a lower energy consumption cost as a result of no heat consumption. A high capital investment balances the operative costs due to the relatively short life of membranes and its high replacement cost (Bartholomew, Siefert and Mauter, 2018; Caldera, Bogdanov and Breyer, 2016)necessary to meet increasing future global water demand, can be powered solely through renewable energy. Hybrid PV–wind–battery and power-to-gas (PtG. Therefore, the capital investment of SWRO technology almost duplicates (1.95:1) the investment required for thermal technologies (see **Figure 31**).

FIGURE 31.

COMPARISON OF CAPITAL INVESTMENT COST FOR SEA WATER DESALINATION TECHNOLOGIES (USD)



Source: authors.

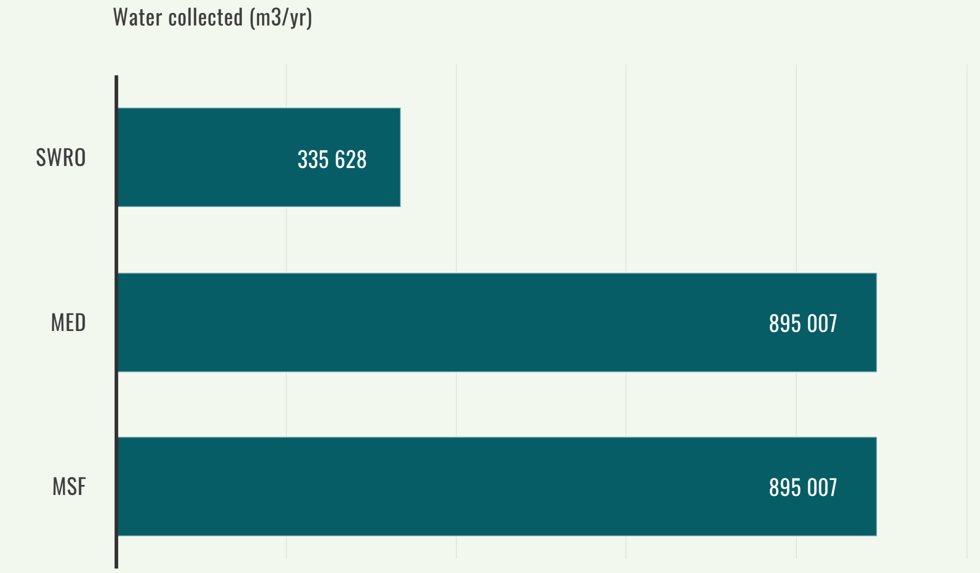
On the other hand, reverse osmosis technologies are more efficient than thermal technologies in seawater consumption for processing. This is because MSF and MED, as thermal technologies, consume heat (transported as mid to high pressure steam) in addition to electricity. Consequently, the amount of water that must be collected to produce 0.35 MLD (105 000 cubic meters per year) reached more than 700 000 cubic meters per year for thermal technologies, while for reverse osmosis this value was almost 1/3 of this value (see **Figure 32**).

In this particular case, all systems will be supplied with seawater in addition to water recirculated from power plants, therefore, seawater will be amply available. Notwithstanding, one of the main consequences of this difference in water consumption is waste production, specifically in the case of brine. Usually, the ratio of brine to seawater feed can range from 1 to 2 for SWRO, while for thermal desalination the ratio is 5 to 8. The brine produced could have a significant effect on the marine environment once discharged due to salinity, temperature, pH, residual chemicals, reactions byproducts, and heavy metals. Hence, the brine salinity and temperature should be considered the major parameters that impact the marine environment. The rule of thumb indicates that brine salinity at the discharge point should not surpass 65-85 g/l, or a temperature of up to 45-50 °C (Elsaid *et al.*, 2020; Liu and Wang, 2017; Mannan *et al.*, 2019; Petersen *et al.*, 2018).

Next, the unit water desalination costs for the three different technology options were calculated. Additionally, values were defined and compared to water price costs for industries and the Seychelles. Overall, it was found that when using the SWRO technology with a selected 35 MLD plant capacity, the highest unit cost equals the water price for water (2.02 USD/m^3) on the island of Mahé. On the other hand, thermal technologies were found to be less expensive, as MED technology was the lowest cost option at 1.08 USD/m³ (**Figure 33**). Currently, the average desalination unit costs range from 0.70 to 3.2 USD/m³ for large to small-scale desalination plants, depending on the costly site-specific intake, discharge, and conveyance peculiarities (Advisian, 2019).

FIGURE 32.

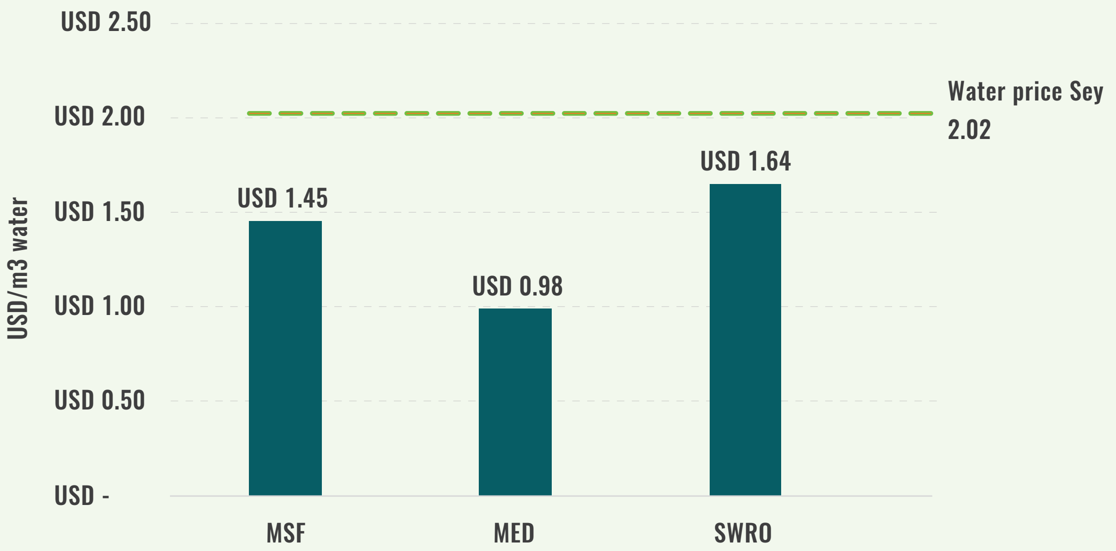
COMPARISON OF SEAWATER CONSUMPTION FOR DESALINATION TECHNOLOGIES



Source: authors.

FIGURE 33.

UNIT COST FOR SEAWATER DESALINATION TECHNOLOGIES



Source: authors.

Table **17** presents a comparative summary of all three desalination technologies based on their electricity consumption, capital investment, and unity desalination cost. Based on the above results, it was proven that MED technology has the best techno-economic performance.

TABLE 17.

COMPARISON OF TECHNO-ECONOMIC RESULTS FOR SEAWATER DESALINATION TECHNOLOGIES

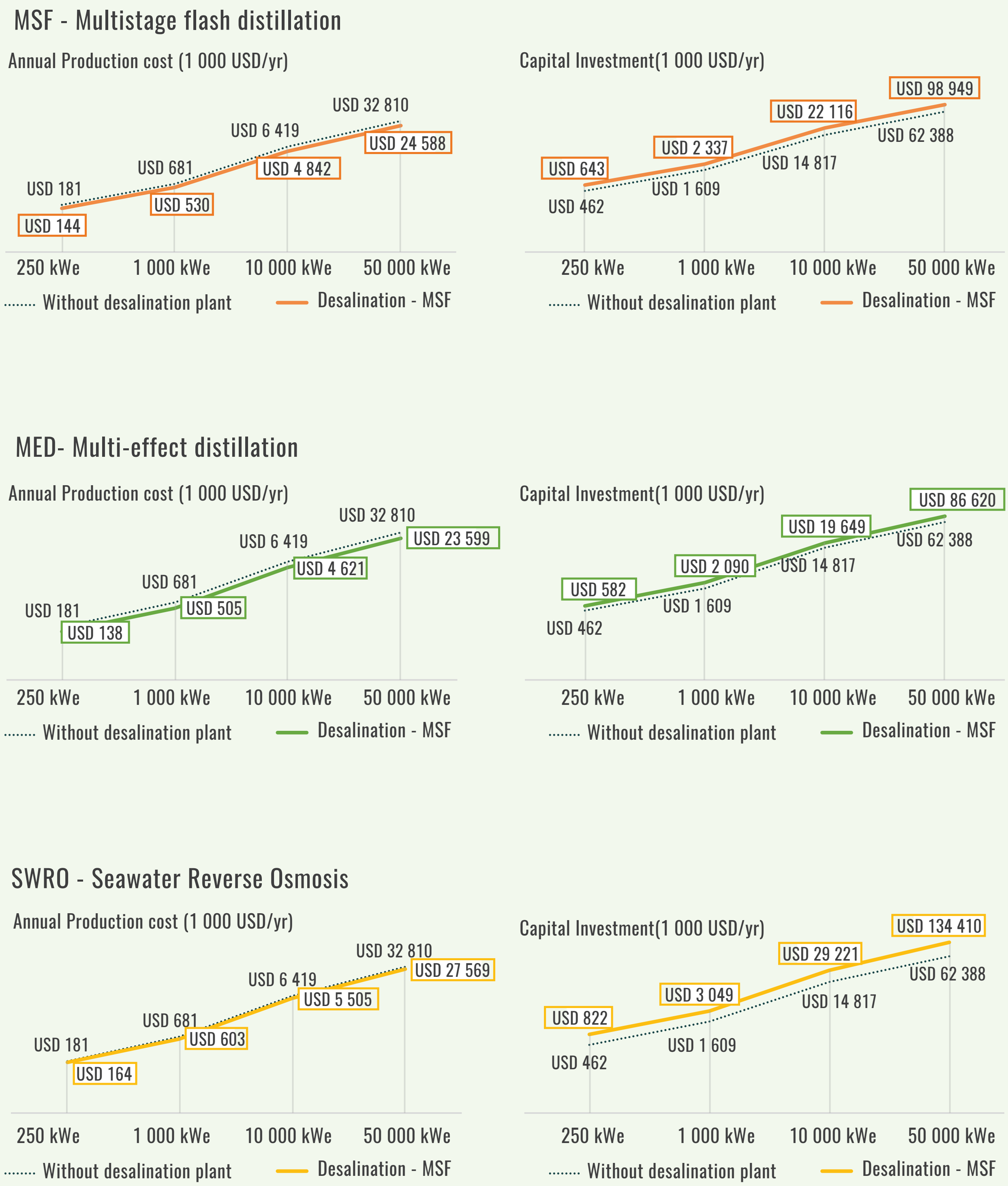
HEADER 1	MSF	MED	SWRO
ELECTRICITY CONSUMPTION	+	+	+++
HEAT CONSUMPTION	++	+++	-
CAPITAL INVESTMENT	+++	+	++
UNIT DESALINATION COST	++	+	+++
MAINTENANCE	++	++	+++
WATER COLLECTED	+++	+++	++
MEMBRANES	-	-	++

Source: authors.

As the next step, the performance of desalination plants integrated into the bioenergy plants using CHP technologies was analysed. Overall, this integration creates synergies between both plants – a desalination plant will provide water, while the CHP plant supplies heat and electricity. In the BEFS assessment case, the main interest focused on the techno-economic performance of bioenergy plants. Therefore, desalination technologies must help reduce annual production costs while minimizing the additional capital investment needed. The results for the three seawater desalination technologies analysed across different plant capacities ranging from 250 kWe to 50 MWe will be presented. This approach will show the performance from small to large generation scales.In the case of MSF desalination,**Figure 34** shows that overall, when using a desalination technology that favours heat consumption over electricity, the annual production costs are reduced by 23 percent, requiring an additional 48 percent capital investment for bioenergy plants. The MED desalination will allow a slightly higher annual cost reduction (26 percent) and a comparatively smaller additional investment (32 percent). Finally, the SWRO option had the worst overall performance. **Figure 35** summarizes the SWRO results that show a mere 13 percent reduction in annual cost; 95 percent additional capital costs are needed.

FIGURE 34.

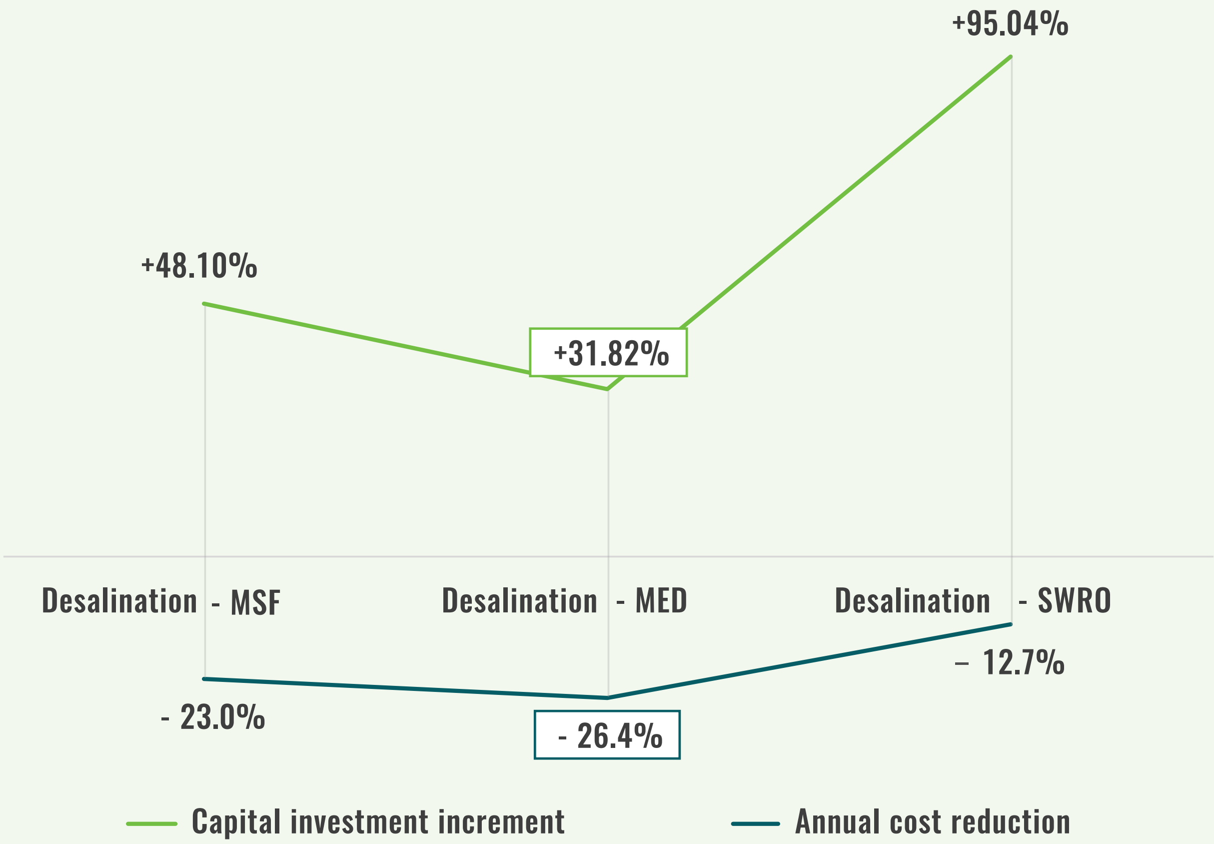
EFFECT OF SEAWATER DESALINATION TECHNOLOGIES ON THE ANNUAL PRODUCTION COSTS AND CAPITAL INVESTMENT OF CHP PLANTS



Source: authors.

FIGURE 35.

SUMMARY OF DIFFERENT DESALINATION TECHNOLOGIES EFFECTS ON THE ANNUAL COST AND INVESTMENTS OF BIOENERGY PLANTS



Source: authors.

Overall, based on the result obtained, it was possible to conclude that self-water production is cost-effective. However, the overall reduction in cost is significant due to the high-water costs in the islands. Furthermore, additional capital investment for bioenergy producers should be considered. Therefore, the most extensive benefits can be obtained by integrating energy plants with MED technology to supply water.

4.3.2 Wet residues based scenarios

All product variations presented in scenarios 1 to 3 are based on the co-digestion of wet residues used to produce biogas. Hence, all of the processing stages were the same for all products. The main characteristics are summarized in **Table 18**, and present the technical decisions made regarding co-digestion, the average monthly temperature effects and maximum attainable plant capacity.

For biogas production, it is customary to combine the locally available options and increase the production rates. This is possible under a scheme named co-digestion, however, this mixture is not completely arbitrary. In order to understand at what ratio different feedstock can be mixed in co-digestion systems, one of the main factors to consider is the C:N ratio of components being taken into account. During AD, the different chemical components of feedstock (i.e., C, H, N, O) are used selectively by different digestion bacteria, where specific ratios of organic matter (carbon) to nitrogen are essential for optimal digestion and avoiding inhibitory effects. In this sense,

TABLE 18.

SUMMARY OF WET RESIDUES QUANTITIES IDENTIFIED AS AVAILABLE

FEEDSTOCK TYPE	TYPE	RESIDUE	AMOUNT (TONNES/YR)	BIOGAS YIELD (M3 BIOGAS/T FRESH)	C/N
CROP RESIDUES	BANANA	PSEUDOSTEM	3 346	10	27
		LEAVES	357	102	
		PEELS	496	49	
LIVESTOCK RESIDUES	PIGS	MANURE	4 195	63	6.45
	LAYERS	MANURE	993	20	7.33
	BROILERS	MANURE	1 932	20	
	CATTLE	MANURE	310	19	25
BIODEGRADABLE WASTE	CLASS 1	MSW + COMMERCIAL	4 836	142	23.78
	CLASS 2	COMMERCIAL/HOTELS	2 510	130	23.78
	CLASS 4	LIQUID - SEWAGE SLUDGE	28 314	26	18.06

Source: authors.

C:N ratios higher than 23:1 are likely to be unsuitable for optimal digestion, while rates below 10:1 might inhibit the digestion process (Marchaim, 1992).

Co-digestion in biogas production requires using one of these options as the main co-digestion feedstock, which helps control the carbon/nitrogen C:N ratio of mixture and ensures efficient digestion. Literature on the subject suggests that a C:N ratio of 30 is optimal (Kangle *et al.*, 2012). Because of their availability and characteristics, the best candidates were found to be the combination of manure residues and sewage sludge. Finally, the sewage sludge was selected because the available volumes were four times higher than all of the manure combined, thus ensuring its dominant role as the main co-digestion feedstock. .

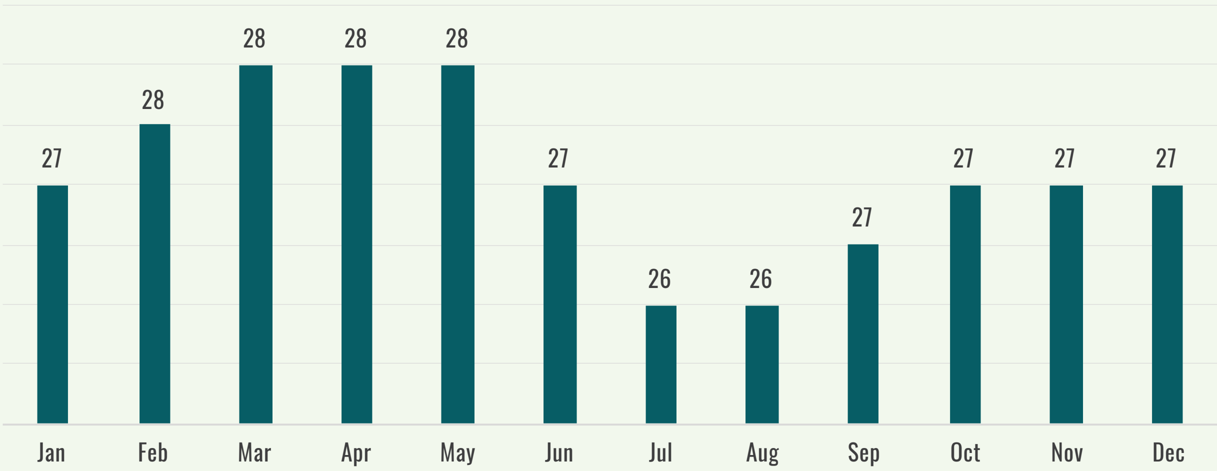
The average monthly temperature in the Seychelles ranges from 26 to 28 °C (**Figure 36**). An appropriate temperature is essential for AD. As a rule of thumb, a digester temperature of 30-32 °C and the sufficient amount of time required for the biological adaptation of bacteria would yield adequate digestion (Wang *et al.*, 2019). A mesophilic regimen grants more stable biological process conditions with an optimal temperature of 35-40 °C and an average HRT of 28 days. However, the digestion operation can happen faster and produce slightly more biogas when using a thermophilic regimen. This process reduces the HRT to 13 days, which demands a digestion temperature increase of 55-60 °C.

An initial calculation has shown that the thermophilic option consumes 66 percent more energy than the mesophilic option. However, smaller digestor volumes and water quantities under the thermophilic option would yield a 15 percent capital cost that is lower than the mesophilic option, considering that most of the analysis scenarios were designed to produce energy (see **Figure 37**).

This will be readily available to meet the biogas production needs. Therefore, the thermophilic option was selected for AD.

FIGURE 36.

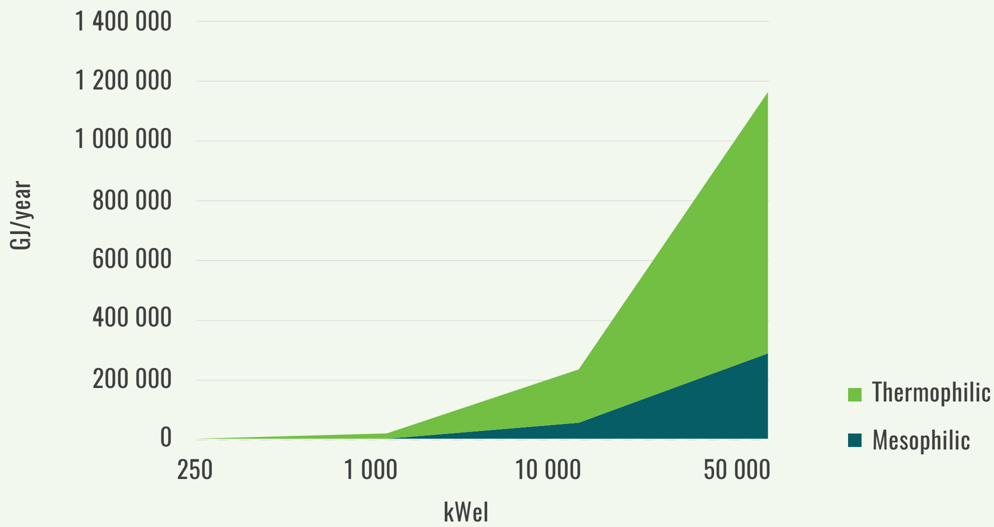
AVERAGE MONTHLY TEMPERATURE VARIATION IN SEYCHELLES



Source: adapted from (climatestotravel, 2020).

FIGURE 37.

ENERGY PERFORMANCE COMPARISON OF THERMOPHILIC AND MESOPHILIC OPERATION MODES



Source: authors.

Based on the quantities available and conditions needed for optimal co-digestion, the mixture would have 47 percent total solids content – out of this, 50 percent would be volatile solids (VS) available for digestion. The digestion mixture's biomethane potential (BMP) was then calculated as 347 m^3 CH_4/t VS.

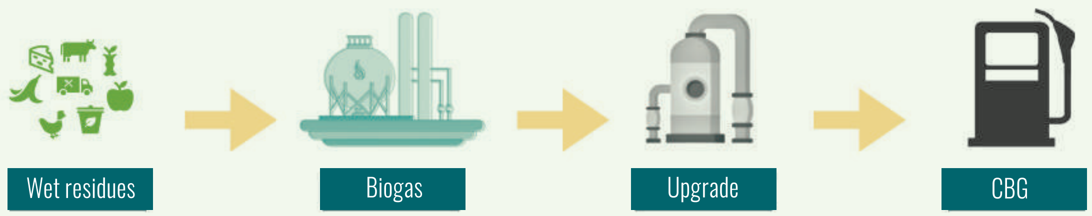
Based on the total combined feedstock identified as available (47 336 tonnes/year), it is feasible to produce a maximum total of 19 000 m^3 biogas/day (see **Table 19**). In practice, it is uncertain whether this total quantity will be finally accessible. Therefore, it was decided to analyse and compare it for its stereotypical plant capacities ranging from 1 333-19 333 m^3 biogas/day to account for the different accessibility rates. Moreover, as biogas is not the final product, the equivalent capacities used in scenarios 1-3 were summarized in **Table 14** for CBG, electricity, as well as heat and electricity.

4.3.2.1 Scenario 1. Wet residues to CBG

In scenario 1, wet residues are converted to biogas using AD technology. The biogas is later purified through an upgrading process, to remove the largest part of other gases different from methane. The obtained mixture is finally compressed to obtain CBG. This scenario assumes that the CBG will be used by automobiles converted to run natural gas (see **Figure 38**). During the last decade, conversion costs have been reduced from 12 000 USD to 750 USD. Thus, locally produced CBG might be a suitable solution to replace imported gasoline for local Seychellois vehicles, to be sold at 0.84 USD/m^3. ***Figure 39*** shows the unit production cost for biogas production plus upgrading to CBG and transport using a pressurized pipeline from the biogas plant to Victoria City. Plant capacities are presented in m^3 Methane/day, as methane is the main component of CBG. Thus, it demonstrates that at 0.837 USD/m^3 (of methane) selling price, the CBG should produce more than 800 m^3 methane/day to produce at a competitive cost.

FIGURE 38.

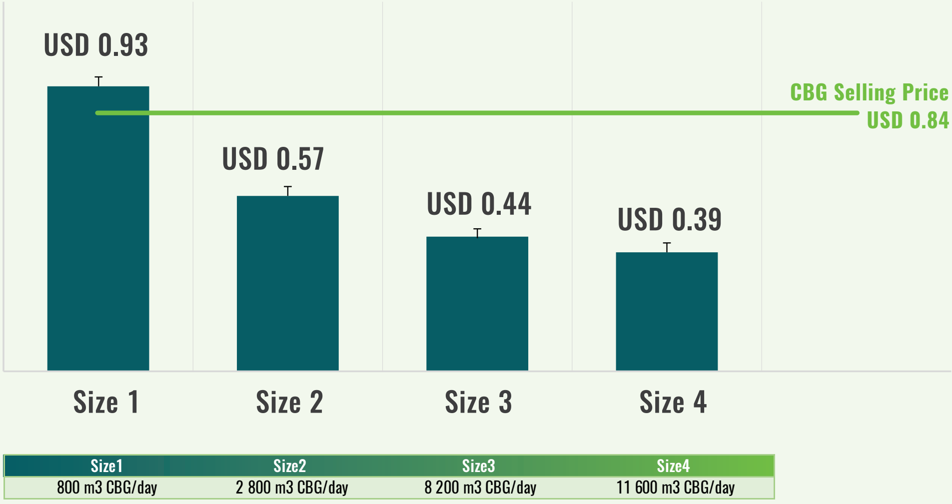
PRODUCTION SCHEME OF SCENARIO 1



Source: authors.

FIGURE 39.

UNIT PRODUCTION COSTS OF CBG PRODUCTION

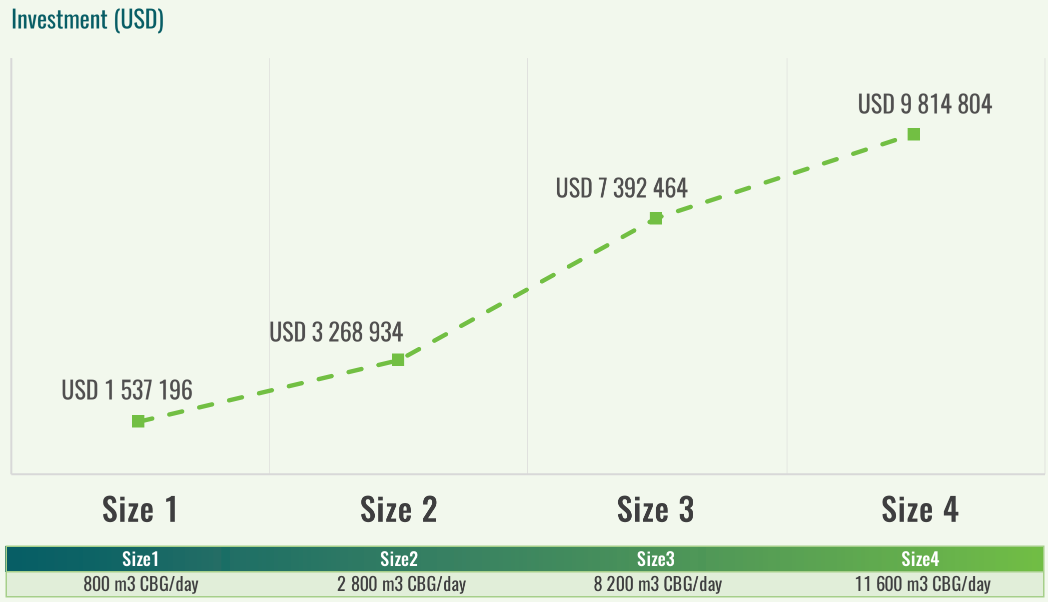


Source: authors taken from BEFS RA biogas industrial tool.

Due to the combined collection costs of all co-digested feedstock, 2 USD/tonnes of the mixture were reached. The largest contributor to production costs was capital investment. From this standpoint, this item will range from 1.5-9.8 million USD, for CBG production ranging from 800 to 11 600 m[3] methane/day (see **Figure 40**).

FIGURE 40.

CAPITAL INVESTEMENT FOR COSTS CBG PRODUCTION



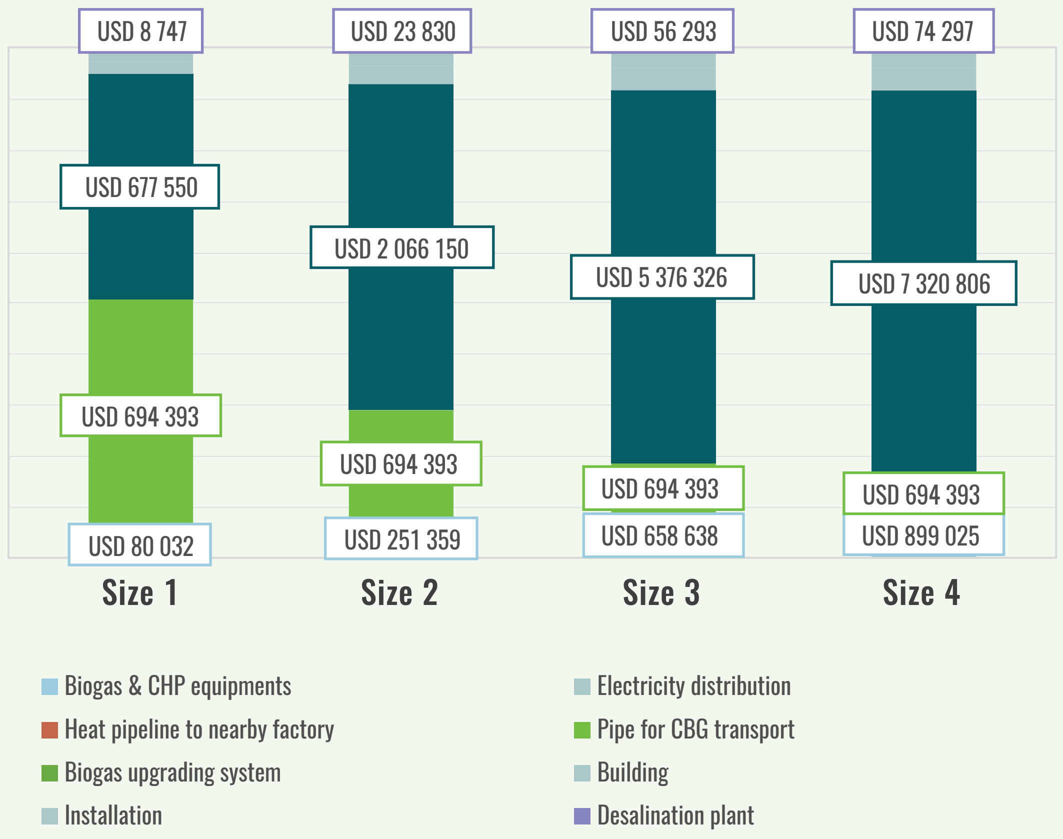
Source: authors taken from BEFS RA biogas industrial tool.

In principle, capital investment costs seem high, mainly justified by the investment needed for upgrading biogas (see **Figure 40**). While the equipment for biogas production costs ranges from 80 to 899 000 USD, the biogas upgrading cost is from 677 000 to 7.3

million USD. Gas purification and compression is technically a complex task requiring a high-pressure operation and expensive units, which explains the magnitude of the cost (Nguyen *et al.*, 2020; Wang *et al.*, 2020). Numerous examples of WWTPs have become net energy producers, necessitating other high-value applications for surplus biogas. A globally emerging trend is to upgrade biogas to biomethane, which can then be used as town gas or transport fuel. Water, organic solvent and chemical scrubbing, pressure swing adsorption, membrane separation, and cryogenic technology are commercially available CO_2 removal technologies for biogas upgrade. Although water scrubbing is currently the most widely applied technology due to low capital and operation cost, significant market growth in membrane separation has been seen over the 2015–2019 period. Further progress in materials engineering and sciences is expected and will further enhance the membrane separation competitiveness for biogas upgrading. Several emerging biotechnologies to i. It is also worth noticing that the cost of piping CNG to Victoria City is fixed independently of the plant capacity at 694 000 USD. The piping cost is a fixed cost linked to the distance and properties of the substance; in this case, CBG, independent of the volume ultimately transported (Hatfield *et al.*, 2006; Pustišek and Karasz, 2017).

FIGURE 41.

SHARE OF CAPITAL COST INVESTEMENT FOR CBG PRODUCTION



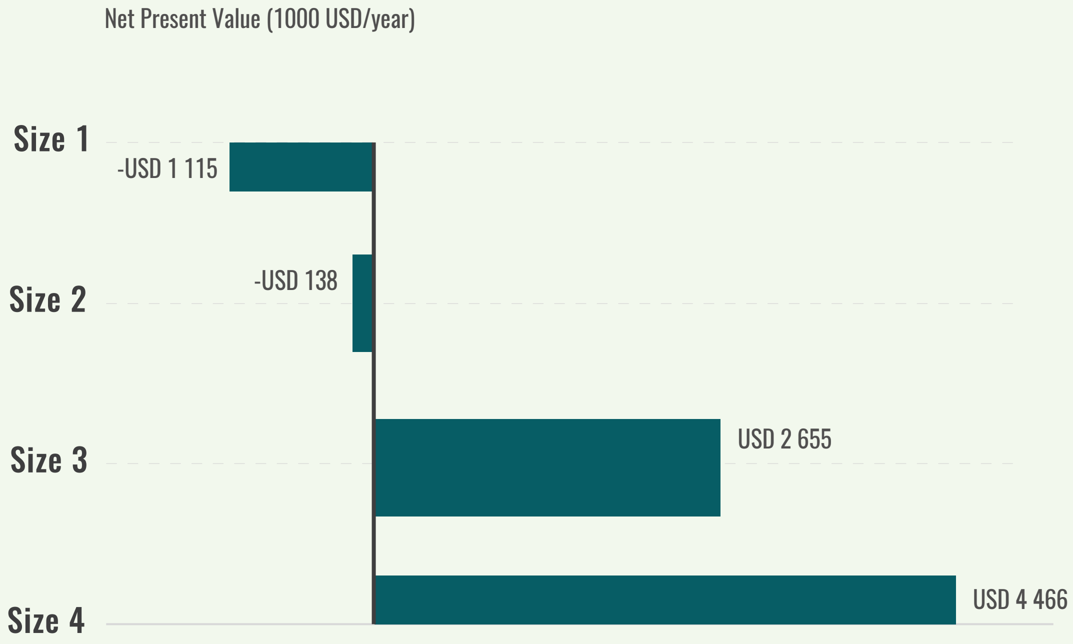
Size1	Size2	Size3	Size4
800 m3 CBG/day	2 800 m3 CBG/day	8 200 m3 CBG/day	11 600 m3 CBG/day

Source: authors.

The profitability assessment has shown that the CBG should produce more than 2 800 m³ methane/day to be profitable over a period of 20 years. Thus, independently of the unit production costs, as this capacity was lower than the CBG selling price, the income would not sufficiently cover the cost of the high initial upfront investment, which turns to a negative profit at the end (**Figure 42**). The profitability under the specific combination of feedstock costs and the CBG selling price resulted in limited profitability. Subsequently, the next step was to obtain a PZM for scenario 1 while simultaneously changing the CBG selling price and combined feedstock costs (see **Figure 43**). As can be seen for most all of the selling prices, the map was dominated by constrained profitability zones. It means that where at least the selling price reaches 1.4 USD/m³ CBG, only some specific plant capacities might be profitable. Thus, in the very best-case scenario (0 USD/tonne feedstock cost, 1.4 USD/m³ selling price), the overall profitability would reach 22 million USD; instead under the worst conditions (30 USD/tonne and 0.2 USD/m³ selling price), losses would reach 24 million USD.

FIGURE 42.

PROFITABILITY RESULTS FOR CBG PRODUCTION



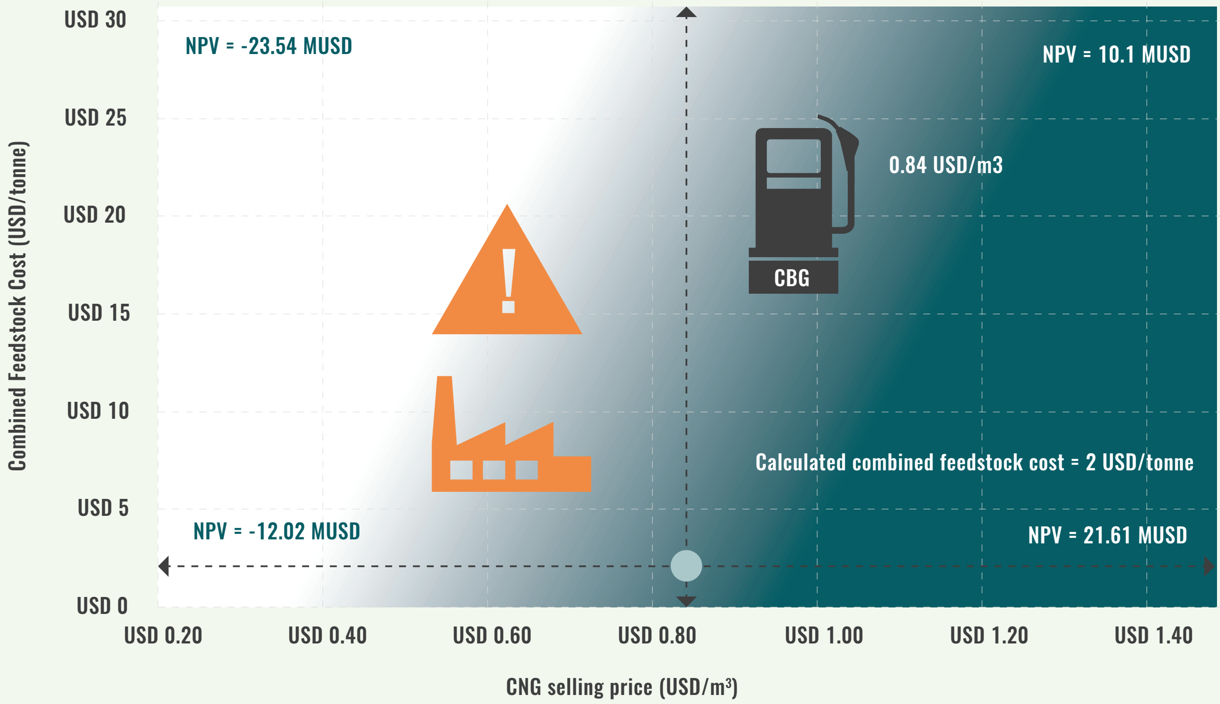
Size1	Size2	Size3	Size4
800 m3 CBG/day	2 800 m3 CBG/day	8 200 m3 CBG/day	11 600 m3 CBG/day

Source: authors taken from BEFS RA biogas industrial tool.

Under the assumption that price variations on a hypothetical CBG market would follow the same trend as fossil fuel over the last several years (see **Figure 44**), a minimum price of 0.78 USD/m³ and a maximum of 0.95 USD/m³ might be expected. Under these conditions, it is assumed that CBG projects would have constrained profitability where a maximum change of 20-0 USD/tonnes could be acceptable.Finally, the potential number of vehicles supplied at the different CBG plant capacities was calculated. To obtain these values, the CBG that a typical vehicle in the Seychelles might consume (see **Table 19**) was identified.

FIGURE 43.

PZM RESULTS FOR CBG PRODUCTION UNDER SEYCHELLOIS CONDITIONS



Source: authors.

TABLE 19.

DATA USED TO ESTIMATE POTENTIAL CONSUMERS SUPPLIED

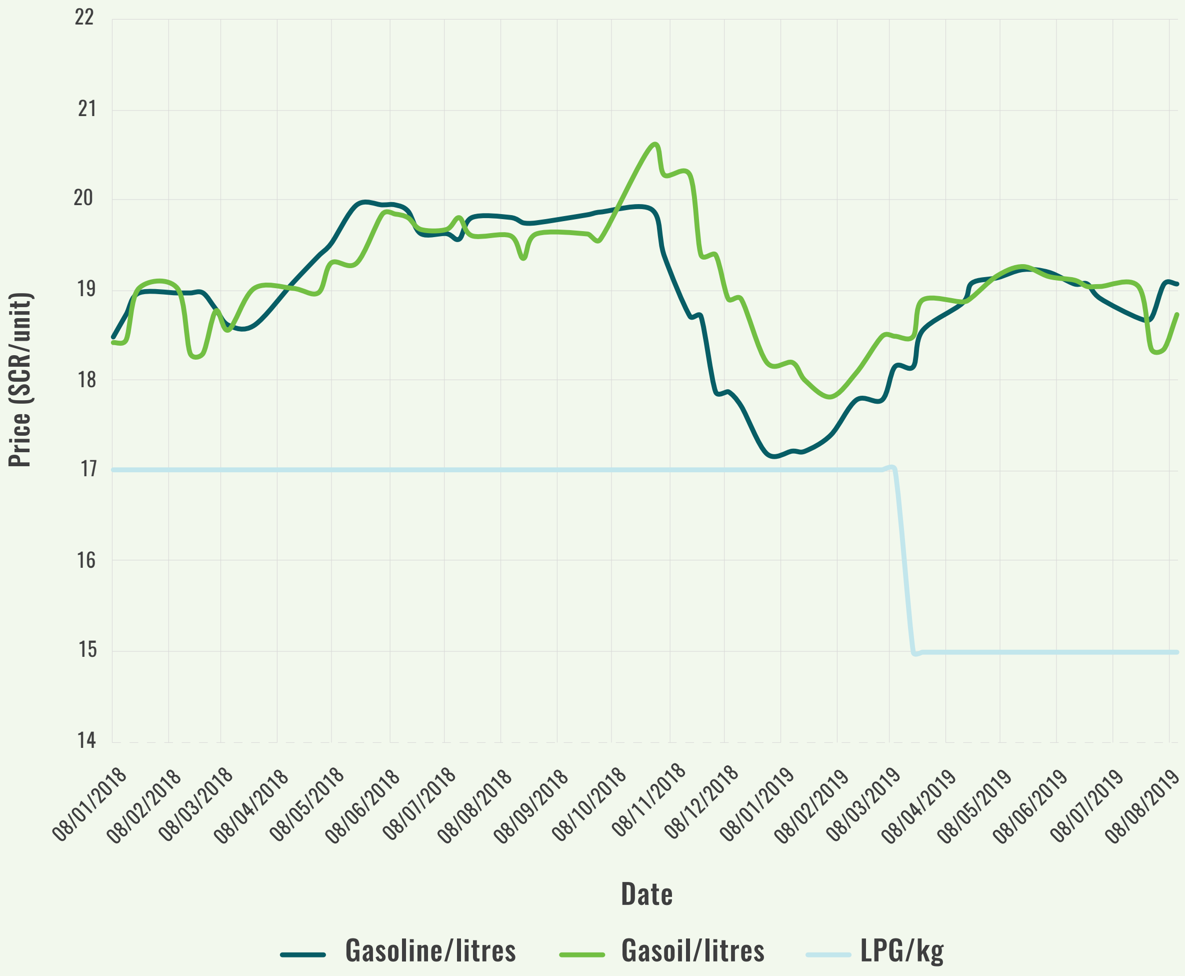
HEADER 1	HEADER 2	HEADER 3
TYPICAL DAILY DISTANCE	19.2	km/day
LHV NATURAL GAS	36.6	MJ/m3
CNG FROM IMPORTED NG 7000 KM, 2020+ PISI	152	MJ/km
TYPICAL WORKING DAYS	262	days/yr
ANNUAL TRAVELLING DISTANCE	5 030.4	km/yr/car
ANNUAL ENERGY CONSUMPTION	764 620.8	MJ/yr/car
ANNUAL CNG DEMAND	20 891.28	m3/yr/car

Source calculated from: (Edwards ***et al.****, 2014; The World Bank, 2020; Who.int, 2013).*

Therefore, these values were obtained for an estimated annual traveling distance of 5 030.4 km/yr/vehicle (see *Table 19*). Here it is shown that it is feasible to supply between 111–333 cars for the largest potential capacity. Making the supposition that the car and 4-wheeled light vehicle population in Seychelles was estimated at 16 810 vehicles, on average the largest plant capacity would use the full 47 336 tonnes/year feedstock potential available. Consequently, it could supply 0.99 percent of all target vehicles.

FIGURE 44.

FOSSIL PRICES VARIATIONS IN SEYCHELLES 2018-2019



Source: adapted from (Seypec, 2021).

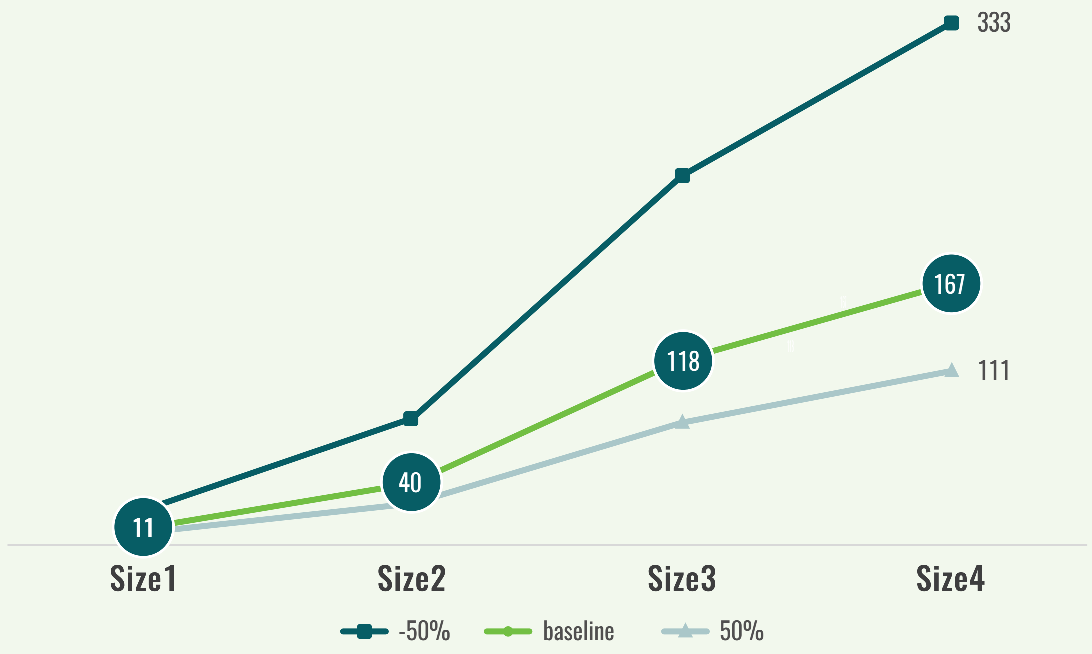
In sum, although it is feasible to have a profitable CBG scheme in the Seychelles, the low potential production and high upfront capital investment cost for its implementation would present challenges.

4.3.2.2 Scenario 2. Wet residues to electricity

In scenario 2, the last stages of scenario 1 were replaced with a CHP system intended to cogenerate heat and electricity from biogas. This scenario assumes that there is no market for cogenerated heat. Next, the heat was converted into additional electricity. The electricity is acquired by the PUC at 0.15 USD/kWh, and subsequently distributed to local households. This means that large amounts of electricity will be available to inject the central grid (see **Figure 46**).

FIGURE 45.

POTENTIAL BENEFITS FROM CBG PROGRAM IMPLEMENTATION IN SEYCHELLES

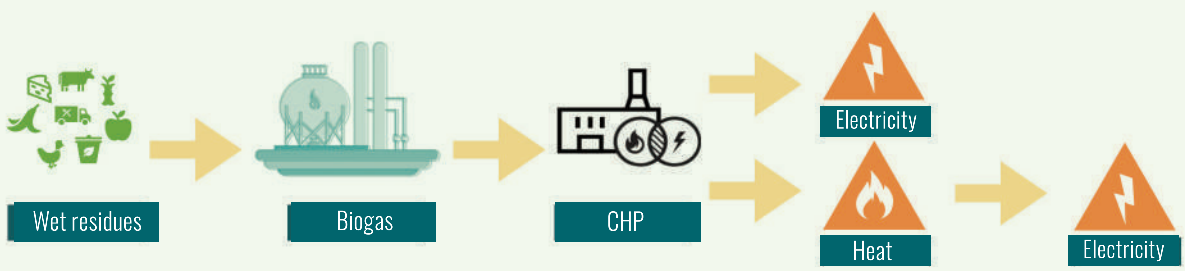


Size1	Size2	Size3	Size4
800 m3 CBG/day	2 800 m3 CBG/day	8 200 m3 CBG/day	11 600 m3 CBG/day

Source: authors.

FIGURE 46.

PRODUCTION SCHEME OF SCENARIO 2



Source: authors.

This scenario uses the electricity tracking mode, which has been designed to prioritize electricity cogeneration rather than heat production. Enough heat was cogenerated to supply the digestion process and the desalination plant, but no heat was available for selling (see **Table 20**).

Figure 47 shows the unit production cost for electricity generation in the Seychelles. Plant capacities are presented in kWe. As shown in the **Table 20**, all electricity generation options could initially be cost-competitive with a tariff of 0.15 USD/kWh.

TABLE 20.

ENERGY BALANCE FOR SCENARIO 2

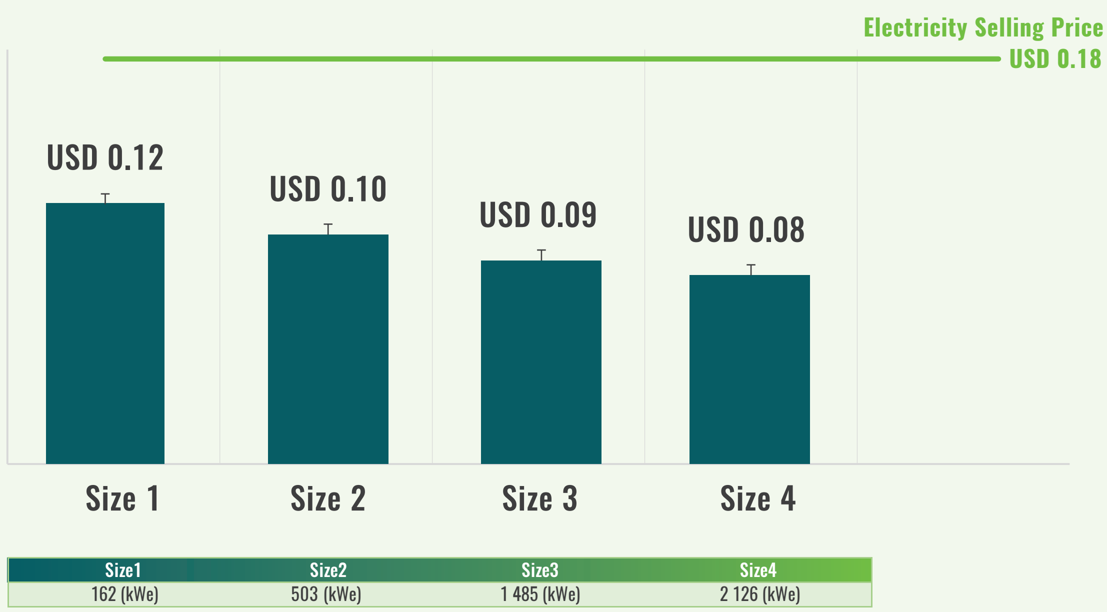
ENERGY BALANCE	UNIT	CAPACITIES *(kWe)*			
		162	503	1485	2126
ELECTRICITY PRODUCTION	kWh/year	1 229 907	3 825 208	6 452 092	9 235 321
HEAT PRODUCTION	GJ/year	-	-	47 821	68 450
ELECTRICITY CONSUMPTION	kWh/year	-65 022	-205 536	-600 267	-854 523
HEAT CONSUMPTION	GJ/year	-3 542	-11 195	-32 699	-46 551
ELECTRICITY AVAILABLE FOR SELLING	kWh/year	-205 536	3 619 672	5 851 825	8 380 798
HEAT AVAILABLE FOR SELLING	GJ/year	-3 542	-11 195	15 123	21 899

Source: authors taken from BEFS RA biogas industrial tool.

Moreover, the capital investment costs ranged from 490 thousand to 5.1million USD for 162 to 2126 kWe. For the same equivalent production scale, capital costs are almost one-fifth of the costs in scenario 1. In this case, the main component of capital costs was the biogas and CHP equipment in addition to the electricity distribution costs (see **Figure 47**).

FIGURE 47.

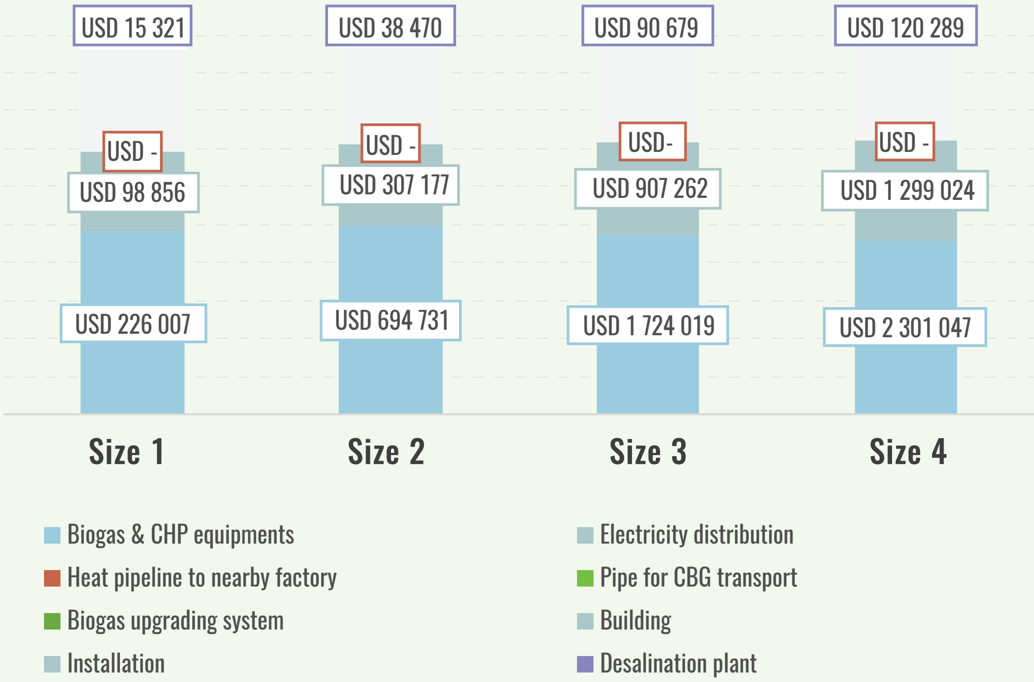
UNIT PRODUCTION COST OF ELECTRICITY FOR SCENARIO 2



Source: authors taken from BEFSRA biogas industrial tool.

FIGURE 48.

CAPITAL INVESTMENT AND SHARE FOR SCENARIO 2



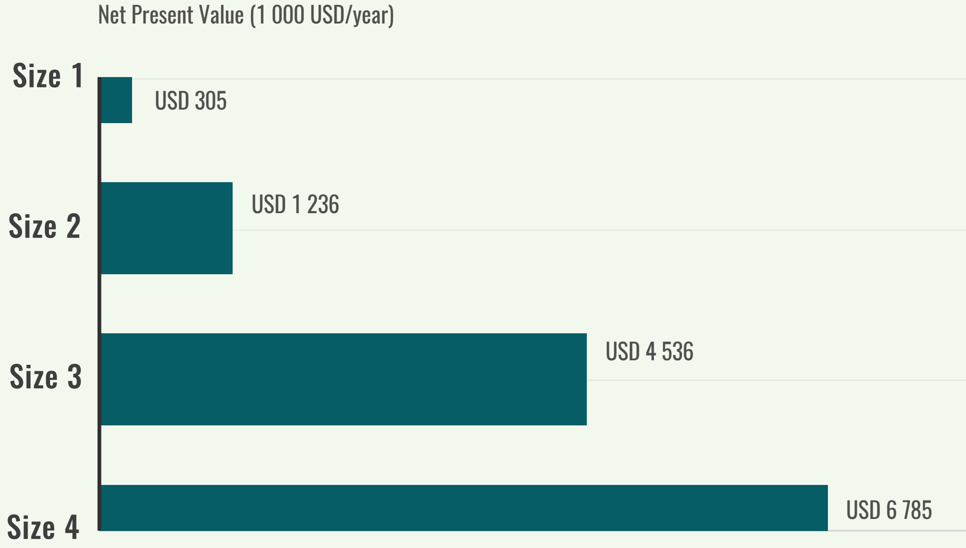
Size1	Size2	Size3	Size4
162 (kWe)	503 (kWe)	1 485 (kWe)	2 126 (kWe)

Source: authors taken from BEFSRA biogas industrial tool.

The profitability assessment has shown that more than 162 kWe must be cogenerated to have a profitable operation for a period of 20 years. Profitability under the specific combination of the feedstock cost and electricity selling price (0.15 USD/kWh) resulted promising, while none plant capacity had a negative NPV (see **Figure 49**).

FIGURE 49.

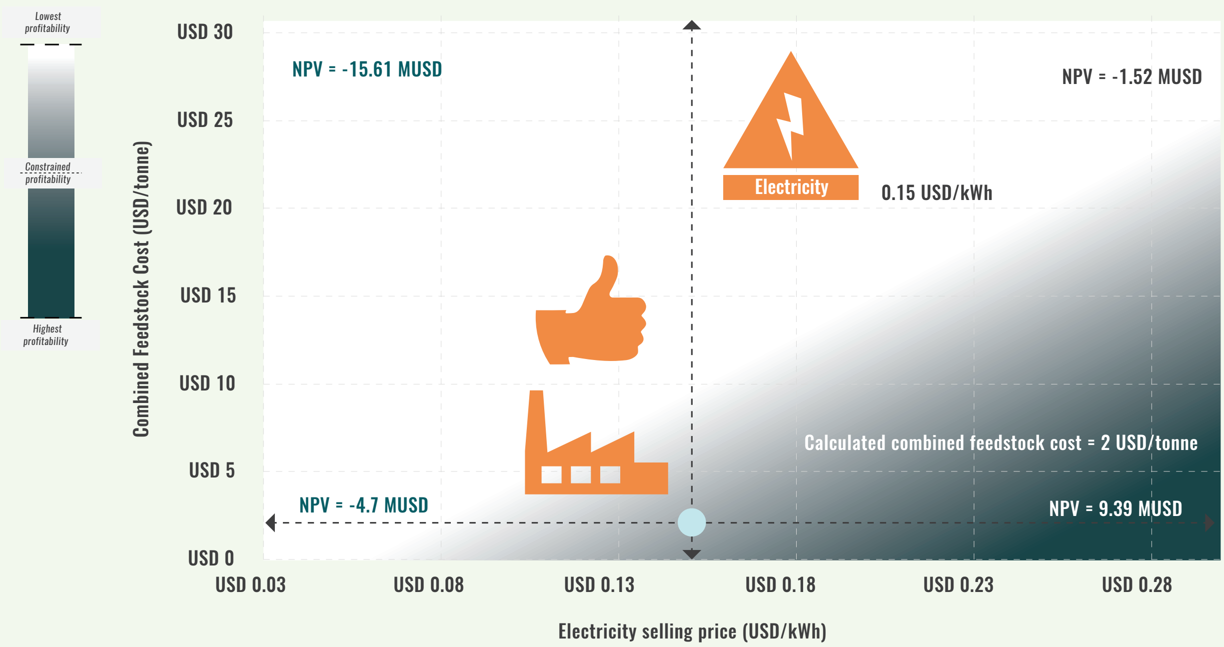
PROFITABILITY RESULTS FOR SCENARIO 2



Size1	Size2	Size3	Size4
162 (kWe)	503 (kWe)	1 485 (kWe)	2 126 (kWe)

Source: authors taken from BEFSRA biogas industrial tool.

FIGURE 50.



MPZM FOR SCENARIO 1

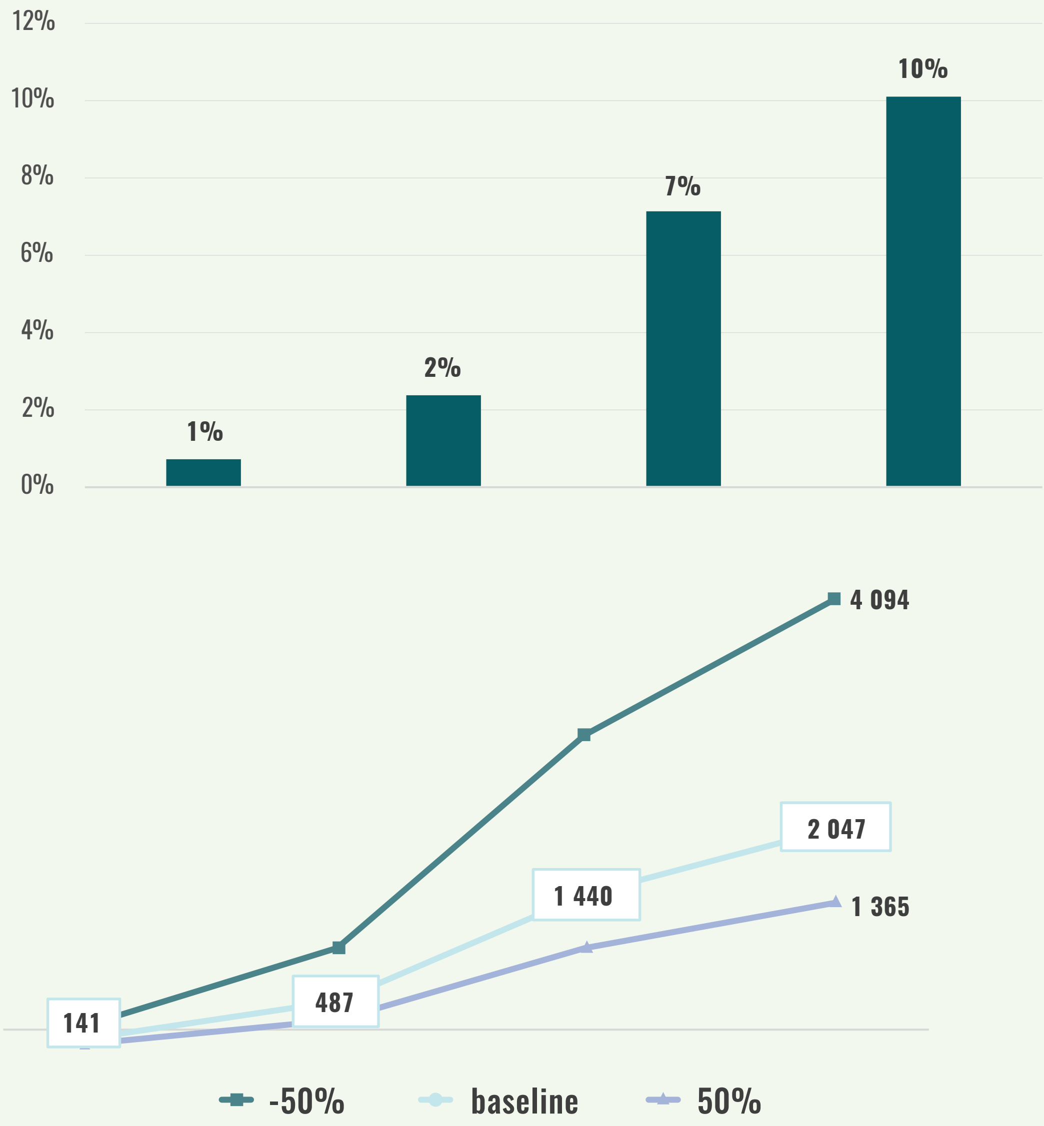
Source: authors.

Next, the PZM for scenario 2 revealed the sensitivity the range of the electricity selling price and combined feedstock costs (see **Figure 50**). The profitability zone (blue colored area) displays high profitability. Thus, in the very best-case scenario (0 USD/tonne feedstock cost, 0.28 USD/kWh selling price), the overall profitability would reach 9.39 million USD. On the other hand, under the worst conditions (30 USD/tonne and 0.03 USD/kWh selling price), losses would reach 16 million USD.Based on the possible price range detailed in the previous sections, it may be concluded that the minimum electricity selling price could reach 0.095 USD/kWh with a maximum of 0.19 USD/m^3. Under these conditions, electricity generation projects would have limited profitability where changes of not more than 0-14 USD/tonnes would be acceptable.

In this regard, the number of consumers potentially supplied by the different electricity generation plant capacities was calculated. The calculations made for the annual electricity consumption per household in the Seychelles resulted as 4 094 kWh/year. The number of households potentially supplied would range on average from 141 to 2 047 households. For example, calculations made for the electricity generation plant installed in Mahé were based on the fact that this island has around 20 000 households. Thus, the largest attainable plant capacity (1 164 kWe) would supply 10 percent of the households in Mahé (see **Figure 51**).

FIGURE 51.

CONSUMERS POTENTIAL SUPPLIED FOR SCENARIO 2



Size1	Size2	Size3	Size4
162 (kWe)	503 (kWe)	1 485 (kWe)	2 126 (kWe)

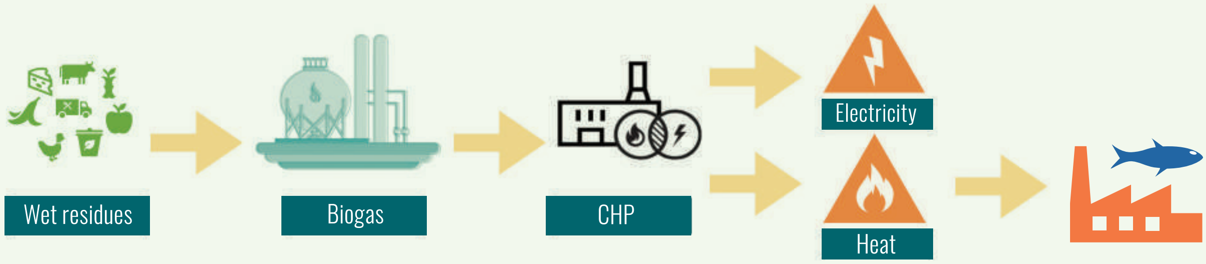
Source: authors.

4.3.2.3 Scenario 3. Wet residues to heat and electricity

Scenario 3 modifies scenario 2, given that it would be feasible to sell the cogenerated heat. In this case, it was assumed that heat would be sold to the canned tuna industry at 5.3 USD/GJ. The remaining electricity will be sold to PUC to be injected into the central grid (see **Figure 52**).

FIGURE 52.

PRODUCTION SCHEME SCENARIO 3



Source: authors.

Therefore, the CHP system will produce heat and electricity using the standard efficiencies (35 percent electricity efficiency and 55 percent thermal efficiency), using the thermal tracking mode. Thus, after discounting the heat consumed by the biogas and desalination systems, there still remains an available portion to sell. (see **Table 21**).

TABLE 21.

ENERGY BALANCE FOR SCENARIO 3

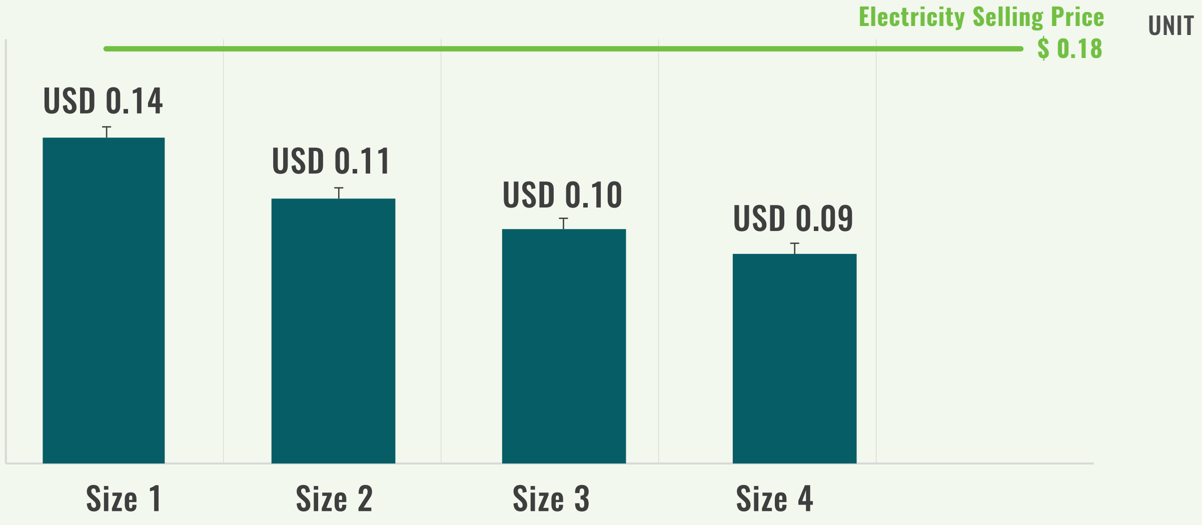
ENERGY BALANCE	UNIT	CAPACITIES *(kWe)*			
		89	275	813	1164
ELECTRICITY PRODUCTION	kWh/year	702 804	2 185 833	6 452 092	9 235 321
HEAT PRODUCTION	GJ/year	-	-	47 821	68 450
ELECTRICITY CONSUMPTION	kWh/year	-65 022	-205 536	-600 267	-854 523
HEAT CONSUMPTION	GJ/year	-3 542	-11 195	-32 699	-46 551
ELECTRICITY AVAILABLE FOR SELLING	kWh/year	637 782	1 980 297	5 851 825	8 380 798
HEAT AVAILABLE FOR SELLING	GJ/year	1 667	5 005	15 123	21 899

Source: authors taken from BEFS RA biogas industrial tool.

Figure 53 shows the unit production cost for heat and electricity cogeneration in the Seychelles. Plant capacities are represented in kWe. Thus, it is shown that based on a 0.15 USD/kWh tariff, the feasibly profitable capacities would be greater than 89 kWe.

Compared to scenario 2, the capital investment costs ranged from 450 thousand to 5.4 million USD for 89 to 1164 kWe, representing a reduction of 10 percent. In this case, the main component of capital costs was the biogas and CHP equipment. Based on the assumption that the factory is potentially supplied with heat and electricity and located within a reasonable radius, the additional distribution costs would represent a mere fraction. Moreover, due to the reduction in the electricity generation capacity, the distribution costs were reduced (see **Figure 54**).

FIGURE 53.



Size1	Size2	Size3	Size4
89 (kWe)	275 (kWe)	813 (kWe)	1 164 (kWe)
463 (kWe)	1 390 (kWe)	4 201 (kWe)	6 083 (kWe)

PRODUCTION COST OF ELECTRICITY FOR SCENARIO 3

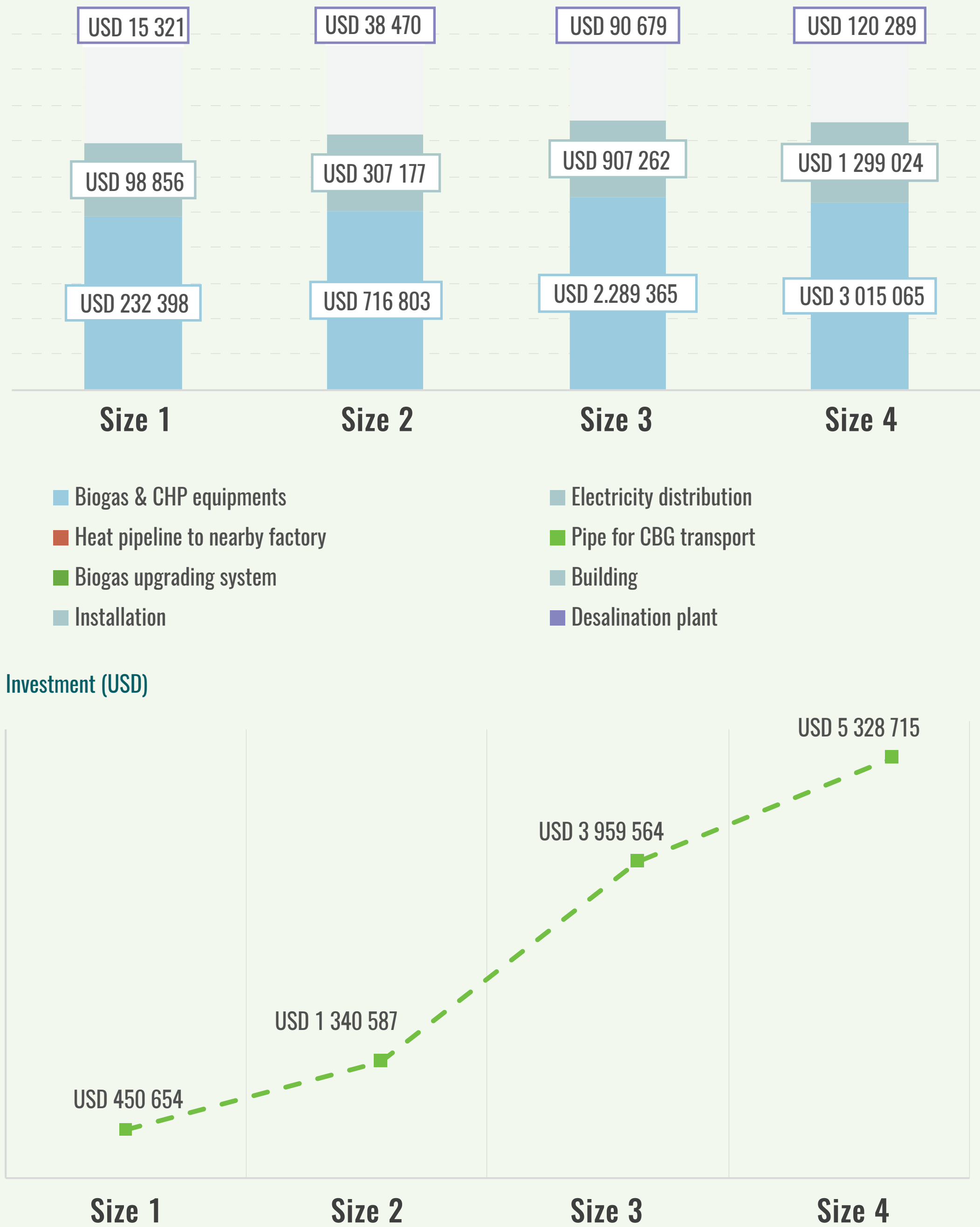
Source: authors taken from BEFS RA biogas industrial tool.

The profitability assessment has shown that the minimum capacity to obtain a profitable operation for a period of 20 years was moved to more than 448 kWe (see **Figure 55**). The profitability under the specific combination of feedstock costs and the electricity selling price (0.15 USD/kWh) resulted limited in profitability. At least two plant capacities had a negative NPV. These results can be seen in the PZM for scenario 3 (see **Figure 56**); the profitable zone leans towards a more limited profitability. Therefore, in the very best-case scenario (0 USD/tonne feedstock cost, 0.28 USD/kWh selling price), the overall profitability would reach 5.13million USD. On the other hand, under the worst conditions (30 USD/tonne and 0.03 USD/kWh selling price), losses would reach 13.5 million USD.

Based on the possible price range detailed in the previous sections, it may be concluded that the minimum electricity selling price could reach 0.095 USD/kWh with a maximum of 0.19 USD/m^3. Under these conditions, electricity generation projects would have limited profitability with changes not exceeding 0-11 USD/tonnes that could be acceptable.

FIGURE 54.

CAPITAL INVESTMENT AND SHARE FOR SCENARIO 3

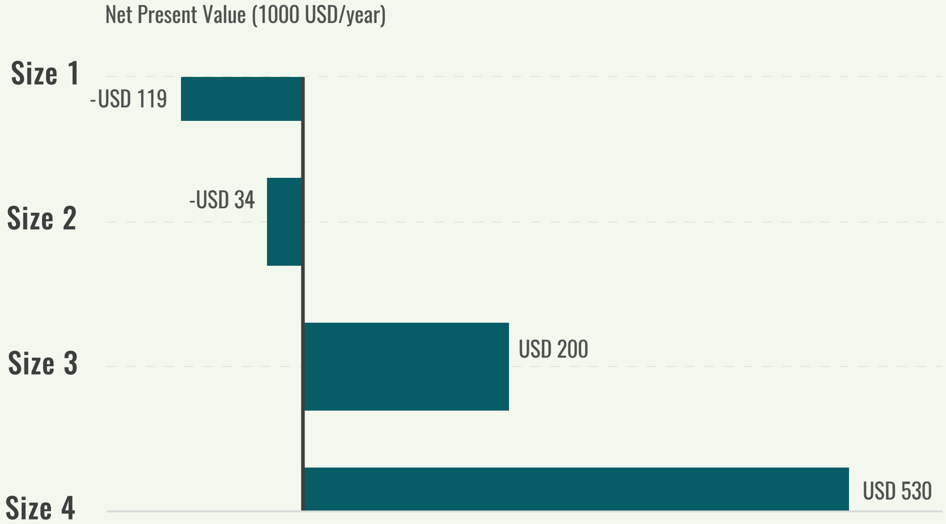


Size1	Size2	Size3	Size4
89 (kWe)	275 (kWe)	813 (kWe)	1 164 (kWe)
463 (kWth)	1 390 (kWth)	4 201 (kWth)	6 083 (kWth)

Source: authors taken from BEFS RA biogas industrial tool.

FIGURE 55.

PROFITABILITY RESULTS FOR SCENARIO 2

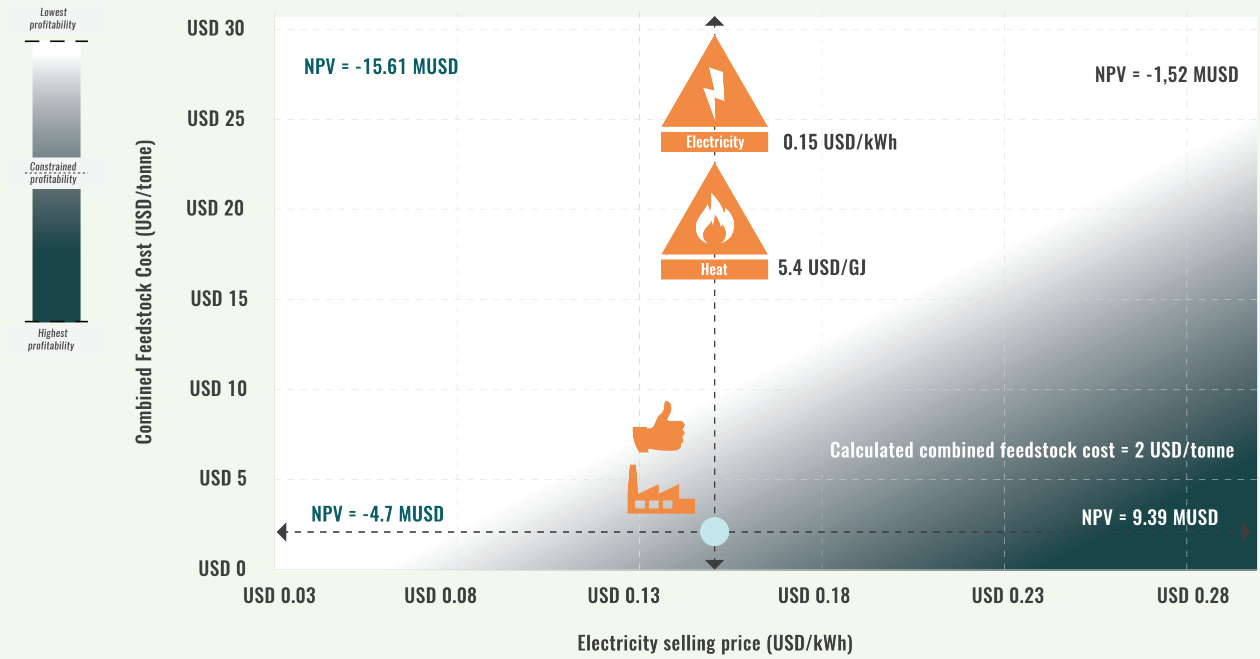


Size1	Size2	Size3	Size4
89 (kWe)	275 (kWe)	813 (kWe)	1 164 (kWe)
463 (kWth)	1 390 (kWth)	4 201 (kWth)	6 083 (kWth)

Source: authors taken from BEFSRA biogas industrial tool.

FIGURE 56.

MPZM FOR SCENARIO 3

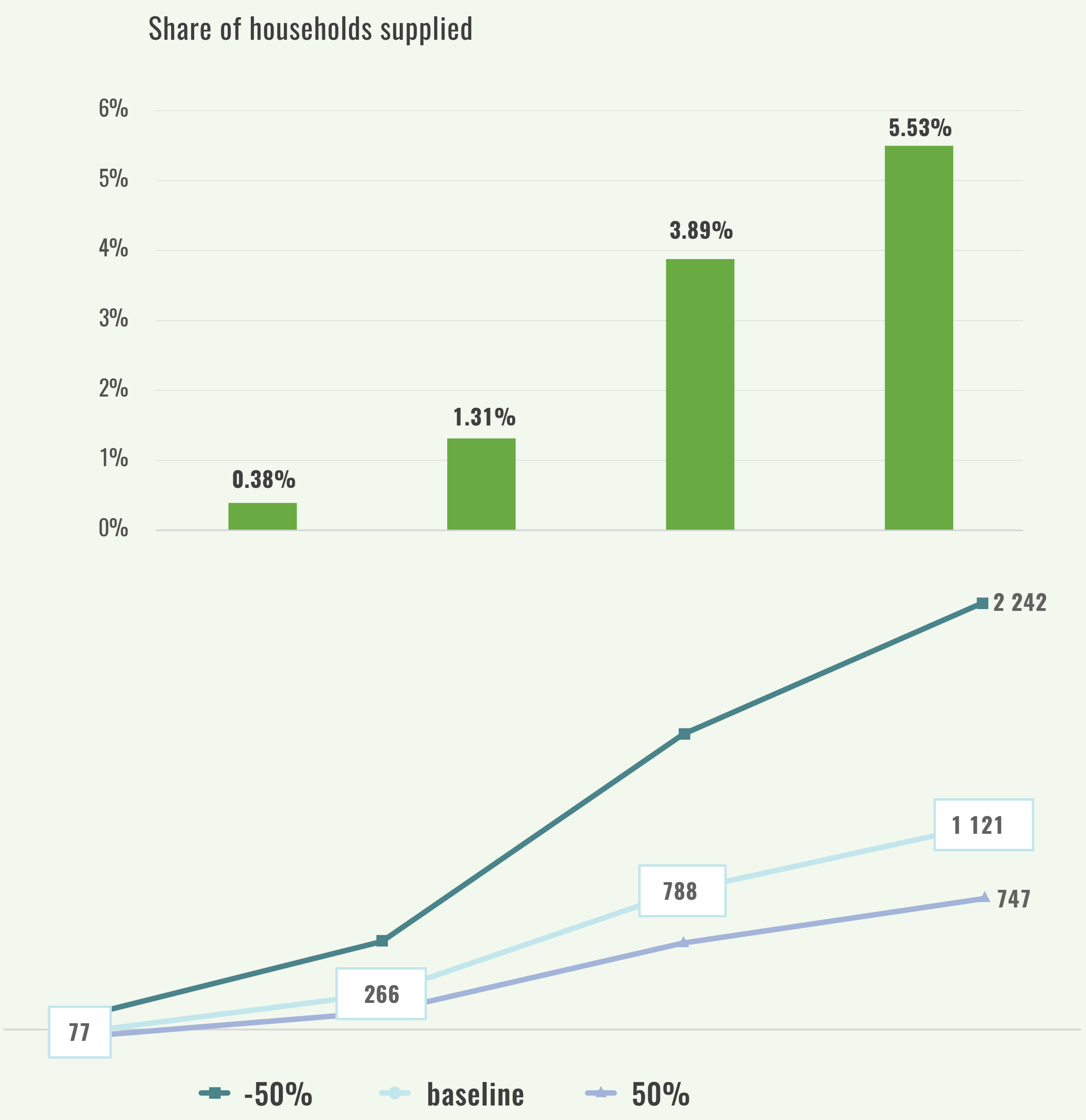


Source: authors.

In this regard, the number of consumers potentially supplied by various electricity generation plant capacities was calculated. Moreover, the energy demand share that might be supplied for a typical tuna factory was also estimated. For the identified annual electricity consumption in the Seychelles, the number of households potentially supplied would range on average from 77 to 1 121 households. The number of households supplied demonstrates that the potential to supply households diminished by 50 percent. Thus, the largest attainable plant capacity (637 kWe) would supply 10 percent of the households in Mahé (see **Figure 57**).

FIGURE 57.

CONSUMERS POTENTIAL SUPPLIED FOR SCENARIO 3



Size1	Size2	Size3	Size4
89 (kWe)	275 (kWe)	813 (kWe)	1 164 (kWe)
463 (kWth)	1 390 (kWth)	4 201 (kWth)	6 083 (kWth)

Source: authors.

The energy that is not converted to electricity and is transferred to a nearby factory was also analysed, so as to define the plant capacities. **Table 22** summarizes the main features and energy demands of a typical tuna factory. The results show that the energy amounts produced using the standard efficiencies for the largest capacity would supply 54 percent of the target demand. The only case where the largest plant capacity could feasibly supply a typical tuna factory's energy demand completely is when the demand is reduced by 50 percent (see **Figure 58**).

TABLE 22.

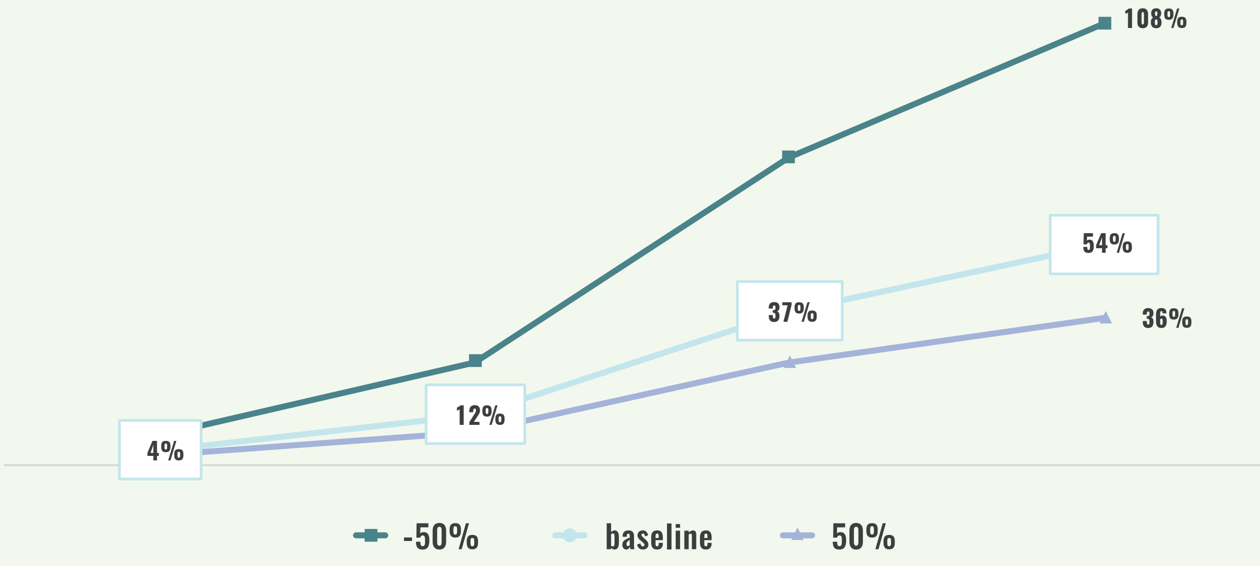
MAIN FEATURES TYPICAL TUNA FACTORY

ENERGY DEMAND - TYPICAL TUNA FACTORY		
HEAT DEMAND	5 623.00	kWh/batch
BATCH SIZE	50.00	tonne/batch
PROCESSING CAPACITY	55 000.00	tonne fresh fish/year
ANNUAL HEAT DEMAND	112.46	kWh/tonne

Source: calculated from (*Quijera, Alriols and Labidi, 2014*).

FIGURE 58.

SHARE OF HEAT DEMAND POTENTIALLY SUPPLIED BY SCENARIO 3



Size1	Size2	Size3	Size4
89 (kWe)	275 (kWe)	813 (kWe)	1 164 (kWe)
463 (kWe)	1 390 (kWe)	4 201 (kWe)	6 083 (kWe)

Source: authors.

4.3.3. GHG emission calculations

GHG emissions savings are calculated for the purpose of understanding the potential impact of bioenergy projects and their contribution to national emission savings targets. The calculations were based on the difference between the GHG emissions produced by each bioenergy project (as presented across the different scenarios) and the emission produced by each target fuel option. When the difference proves to be negative, the project is a sink; otherwise, it might be considered a source, in which case it should be avoided from the emissions perspective.

These calculations were based on the EU-Renewable Energy Directive (RED II), which defines a common framework for promoting and evaluating sustainable bioenergy production from different sources. The bioenergy options included in RED II are transport fuels, electricity, heating, and cooling. More specifically, in the BEFS assessment RED II Annexes V and VI were used for the calculation of bioenergy GHG emissions. The mandatory RED II sustainability and GHG savings criteria for electricity, heating and cooling correspond to the voluntary recommendations for EU member states applied during the period 2010–2020. Calculations were made using the BioGrace-II GHG calculation tool developed to make GHG calculations that are in line with Directive (EU) 2018/2001. This tool is managed by the Netherlands Enterprise Agency (RVO) (European Parliament, 2018; European Parliament and the Council, 2018; Netherlands Enterprise Agency (RVO) and German Institute for Energy and Environmental Research (IFEAU), 2019). In addition, the BEFS techno-economic assessment results provide all of the inputs for calculations.

FIGURE 59.

GHG EMISSIONS FROM THREE DIFFERENT PATHWAYS FOR SCENARIO 1: WET RESIDUES TO CBG

	1	2	3
	Pathway configuration	Pathway configuration	Pathway configuration
Digestate storage	Open digestate storage	Gas-tight digestate storage	Gas-tight digestate storage
Energy provision in digestion	Without off-gas combustion	Without off-gas combustion	With off-gas combustion
All results in g $CO_{2,eq}$ /MJ Biomethane	Total (allocated results)	Total (allocated results)	Total (allocated results)
Cultivation e_{ec}	-6.8	-6.8	-6.8
Upstream emissions	-6.81	-6.81	-6.81
Digester (part of processing e_p)	88.2	1.4	1.4
Anaerobic digestion	88.16	1.45	1.45
Upgrading (part of processing e_p)	26.5	26.5	5.5
Upgrading plus injection into the natural gas g	26.49	26.49	5.49
Transport e_{td}	0.6	0.6	0.6
Transport of subtrates	0.62	0.62	0.62
Land use change e_l or e_{sca} Bonus e_{ccr} + e_{ccs}	0.0	0.0	0.0
Totals	108.5	21.8	0.8

Source: results obtained from BioGrace-II Excel tool – GHG emissions.

Figure 59 presents the GHG emissions estimated for the wet residues to CBG production (Scenario 1). The assessment includes three pathway configurations differentiated by the final digestate storage system (as open or closed) and the off-gases combustion system (as with or without).

Four stages were included in the calculation, as shown in Equation 2.

EQUATION 2

$$\text{Wet residues to Bio-CNG emissions}\left(\frac{gCOeq}{MJbiogas}\right) = \text{Feedstock emissions } (e_{ec}) + \text{Digestion } (e_{p1}) + \text{Upgrading } (e_{p2}) + \text{Transport } (e_{td})$$

Cultivation emissions (e_{ec}) resulted as negative because all feedstock options considered wet agricultural residues are valorized instead of being discarded. The feedstock emissions for all pathways were the same. The processing emissions (e_p) have two components: the first is AD that is mainly impacted by how digestate product is stored (see **Figure 59**), pathway configuration. Pathway is featured by open storage for digestate. This storage system allows for the digestate to decompose and emit volatile matter not converted to biogas as CH4 and N2O, while Gas-tight storage will prevent these emissions. Hence, Pathway 1 has higher emissions in this item than Pathways 2 and 3. In the case of the processing emissions (e_p), these are affected by upgrading and injection to natural gas lines processes. This is an energy-intensive stage, which consumes external energy and therefore all of the energy required to operate the system must be locally sourced while increasing the processing emissions, as all biogas produced is converted to CBG. E_{ps} are also affected by the decision to include an off-gas combustion system. This system will determine how flue gases are handled and is used in Pathways 1 and 2; these pathways have higher emissions in this item than in Pathway 3. The final stage is the transport of substrates stage (e_{td}) under the assumption that the biogas plant will collect all wet residues in Mahé island. Emissions for all pathways were low.

Under the processing conditions defined in the previous sections, it was found that the most feasible pathway is number 2. Therefore, the emission factor for wet residues to CBG via biogas production amounted to 21.8 gCOeq/MJmethane.

FIGURE 60.

GHG EMISSIONS FROM THREE DIFFERENT PATHWAYS FOR SCENARIO 2 AND 3

All results in g $CO_{2,eq}$ /MJ $_{Biogas}$	1 Total (allocated results)	2 Total (allocated results)
Cultivation e_{ec}	**-3.7**	**-3.7**
Upstream emissions	-3.67	-3.67
Processing e_p	**40.7**	**0.0**
Anaerobic digestion	40.66	0,0
Transport e_{td}	**0.3**	**0.3**
Transport of substrates	0.33	0.33
Emissions from the fuel in use e_u	**12.5**	**12.5**
CH_4 and N_2O emissions at final conversion	12.49	12.49
Land use change e_l or e_{sca} Bonus e_{ccr} + e_{ccs}	**0.0**	**0.0**
Totals	**49.8**	**9.2**

Pathway configuration	1	2
Digestate storage	Open digestate storage	Gas-tight digestate storage
Energy provision in digestion	Electricity and heat from CHP	Electricity and heat from CHP

Source: results obtained from BioGrace-II Excel tool - GHG emissions.

Figure 60 presents the GHG emissions estimated for the wet residues to electricity and heat/electricity (Scenario 2 and 3) processes. From a GHG emissions perspective, these two options are equal because in the end they both burn the biogas produced to cogenerate energy. Consequently, the BEFS assessment will analyse the emissions for Scenarios 2 and 3 together. The evaluation comprised two pathway configurations for the digestate storage system (open or closed).

Four stages were included in the calculation, as shown in Equation 3.

Regarding cultivation, emissions (e_{ec}) still appear, as all feedstock options are valorized agricultural residues. EECs for all pathways were the same as in Scenario 1, as was the case for the transport of substrates stage (etd).

EQUATION 3

$$Wet\ residues\ to\ energy\ emissions\ \left(\frac{gCOeq}{MJmethane}\right) = Feedstock\ emissions\ (e_{ec})+$$

$$Digestion\ (e_{p1}) + emissions\ from\ fuel\ in\ use\ (e_{u}) + Transport\ (e_{td})$$

It is worth noting that for the calculation of processing emissions (ep) in the AD of wet residues, the magnitudes were different from those obtained in Scenario 1 because the denominator units were MJ biogas. Due to the fact that all of the energy consumed by the system is self-supplied by the cogeneration system, the only possible emissions source is the digestate product storage; therefore, only the open storage pathway will produce GHG emissions. Finally, the fuel in use (eu) emissions are the CH4 and N2O emissions due to the biogas burning in the CHP system's boiler.

Once the emissions obtained for all steps under the processing conditions were considered, the closest pathway still resulted as number 2. Therefore, the emission factor for wet residues to electricity and electricity/heat via biogas production for Scenarios 2 and 3 amounted to 9.2 gCOeq/MJbiogas.

Table 23 summarizes the emissions factors calculated by using the Biograce II Excel tool and their corresponding values were converted to the units used for plant capacities as in Scenarios 1 to 3.

The next step was to calculate the GHG emissions savings for each plant capacity and scenario. These were calculated by establishing a balance between the GHG emissions from the bioenergy project (with-project) and the GHG emissions from the conventional energy production (without project) as presented in Equation 4. The energy products replaced in these scenarios are motor gasoline, electricity, and heat as steam. Thus, the emission factors collected from scientific literature for the Seychelles were 69.3 gCO_2eq/MJ (motor gasoline), 659.36 gCO_2eq/kWh (electricity), and 76.593 gCO_2eq/MJ (heavy fuel oil).

GHG emissions net balance = Emissions with project (biofuel production and usage) – Emissions without project (business as usual)

EQUATION 4

Figure 61 summarizes the GHG emissions savings for all plant capacities of Scenarios 1–3. In Scenario 1, CBG is intended for replacing gasoline as fuel for vehicles. Overall, with this alternative the emissions were the highest among the wet-residues based options, due to the increased emission factor obtained because of the need to use external fuels to power this alternative. However, the potential GHG emissions savings were also the highest among all the wet residues options. For example, the largest plant capacity might save around 5800 tCO_2 eq/year by replacing motor gasoline with CBG locally produced in the Seychelles.

TABLE 23.

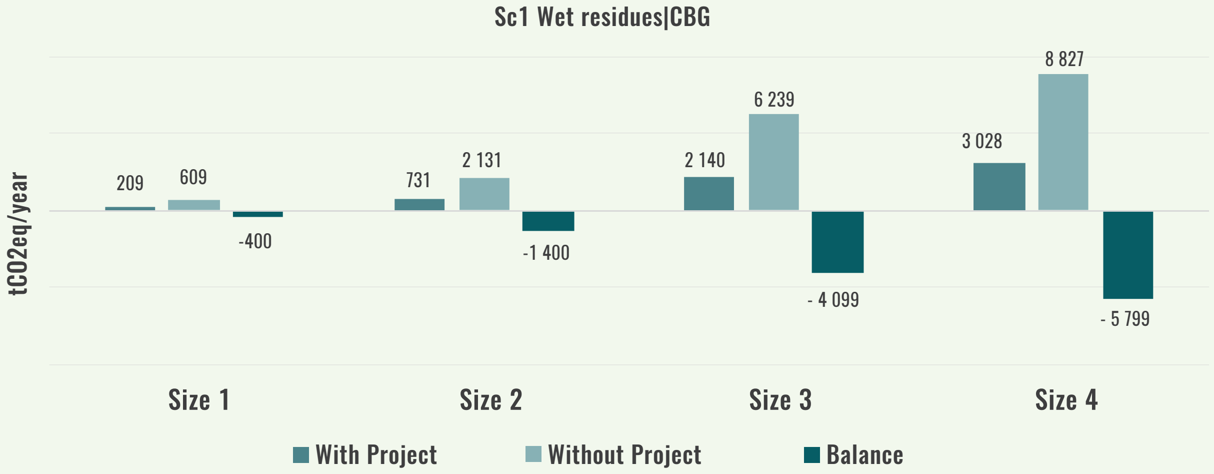
SUMMARY OF EMISSION FACTOR CALCULATED FOR SCENARIOS 1 TO 5

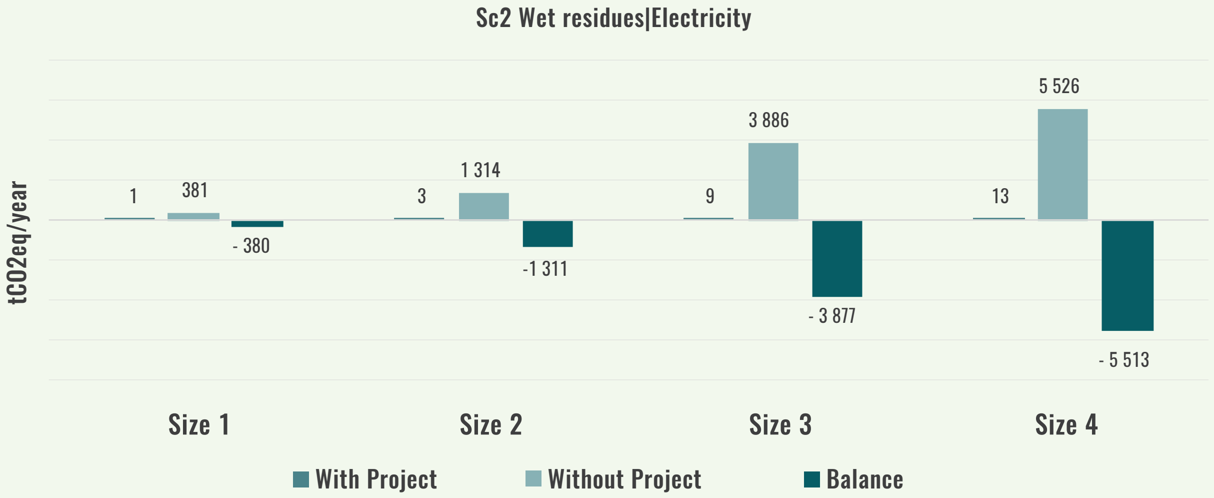
SCENARIO	VALUE	UNIT BIOGRACE	VALUE	UNIT CONVERTED
SC1 WET RESIDUES|CNG	21.8	gCO2/MJ CNG	0.9	kg CO2/m3
SC2 WET RESIDUES|ELECTRICITY	9.2	gCO2/MJ biogas	1.5	g CO2/kWhel
SC3 WET RESIDUES|ELECTRICITY&HEAT	9.2	gCO2/MJ biogas	1.5	g CO2/kWhel

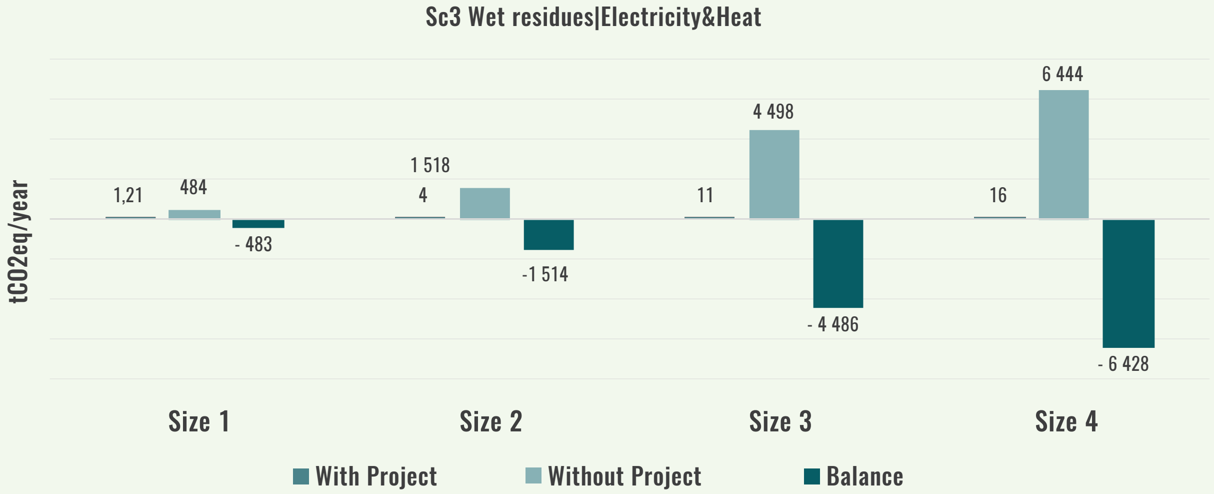
Source: authors.

FIGURE 61.

GHG EMISSION SAVINGS FOR SCENARIOS 1 TO 3







Source: authors' calculations.

Regarding Scenarios 2 and 3, although the emission factor was calculated as the same for both alternatives, the energy forms replaced were slightly different.

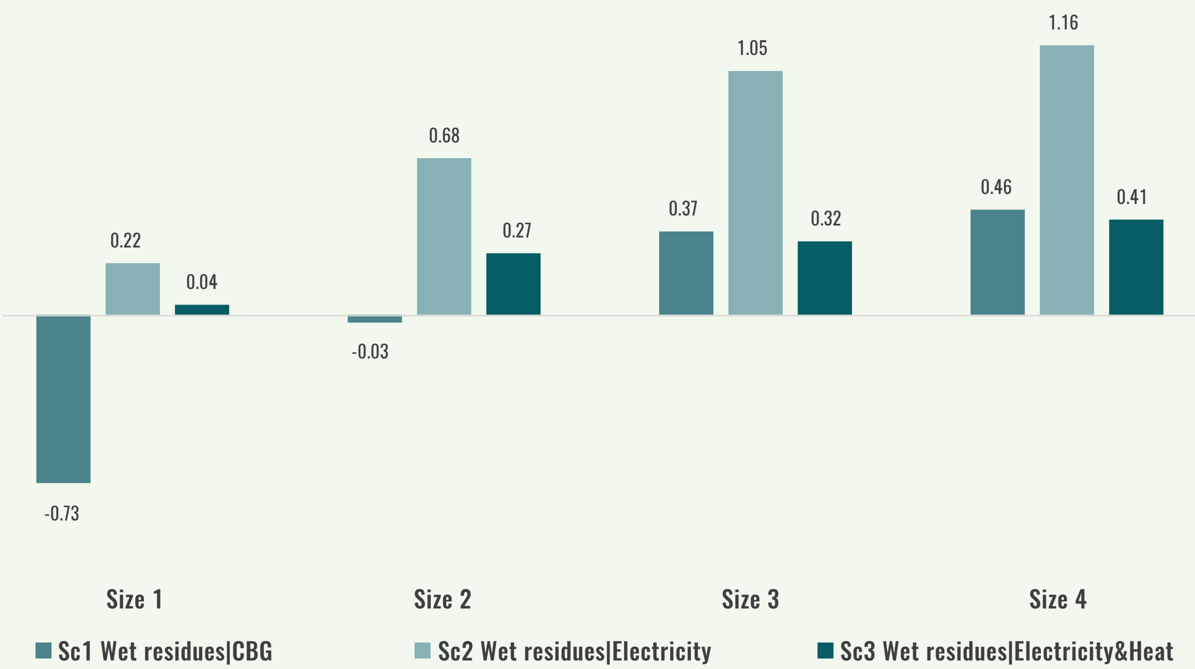
In sum, Scenario 2 replaces electricity only, and Scenario 3 replaces both electricity and heat, while their GHG emissions are slightly different. Based on their emission factors, electricity generation in the Seychelles is more emission-intensive than steam production based on heavy fuel oils. Accordingly, the electricity and heat amount produced for each plant capacity and scenario will impact the total emissions produced. As a result, the GHG emissions savings for Scenario 2 were 5 513 tCO_2 eq/year and for Scenario – 3 934 tCO_2 eq/year for the largest plant capacity.

4.3.4 Comparison of scenarios results and selection

Finally, the results for all of the scenarios were compared according to their techno-economic and GHG emissions savings performance. Moreover, the BEFS assessment considered the difference in production scales so as to make a fair comparison, while the appropriate indexes were used for the analysis . The same criteria will be used to propose the combination of feedstock and technologies that should be considered in the Seychelles to valorize locally available resides and produce energy.

FIGURE 62.

PROFITABILITY INDEX RESULTS FOR SCENARIOS 1 TO 5

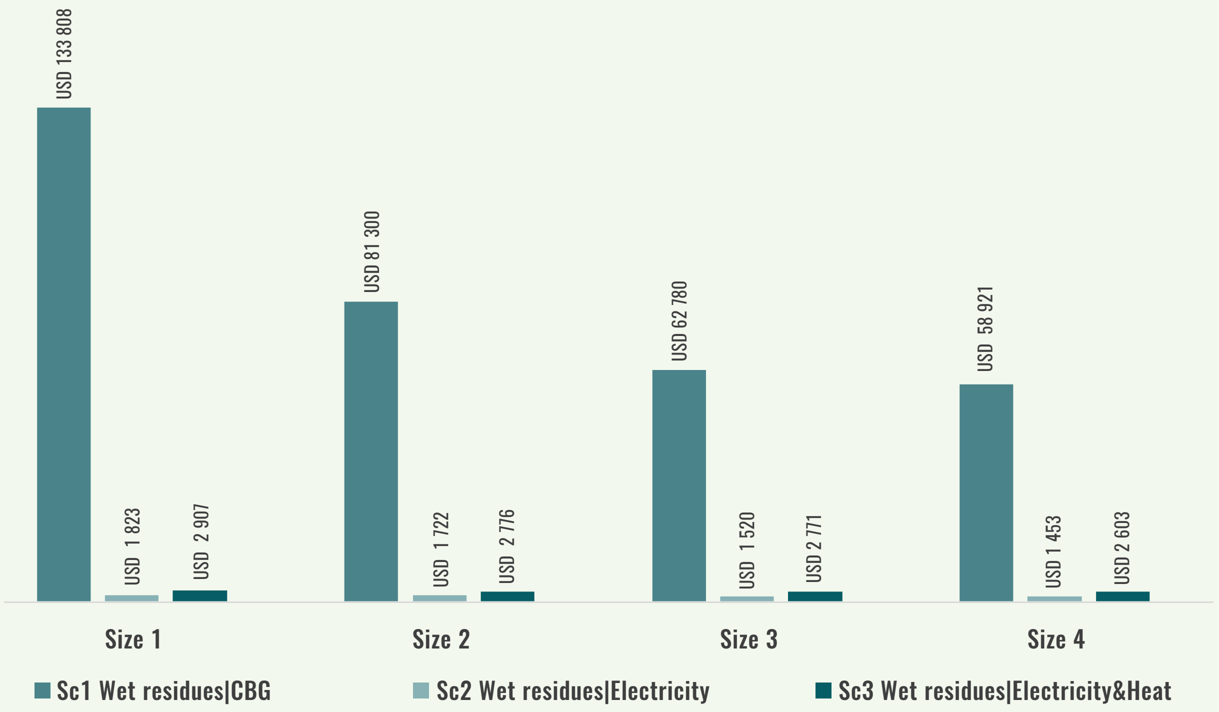


Source: authors.

The first indicator used was the Profitability Index. This index measures the US dollar profit per US dollars invested and measures how the invested capital would yield a profit for investors. **Figure 62** summarizes the profitability index results. Overall, the highest profitability index was Scenario 3 (wet residues to electricity) was the overall champion with a 1.16 USD profit per US dollars invested. Regarding Scenarios 1 and 3, the high upfront investment costs required for purifying and transporting CBG in Scenario 1 reduce its profitability and prove that this alternative would not be appealing to investors, and lack of appealing of selling heat in Seychelles in Scenario 3 discarded these options.

FIGURE 63.

INVESTMENT PER CUSTOMER RESULTS FOR SCENARIOS 1 TO 5



Source: authors.

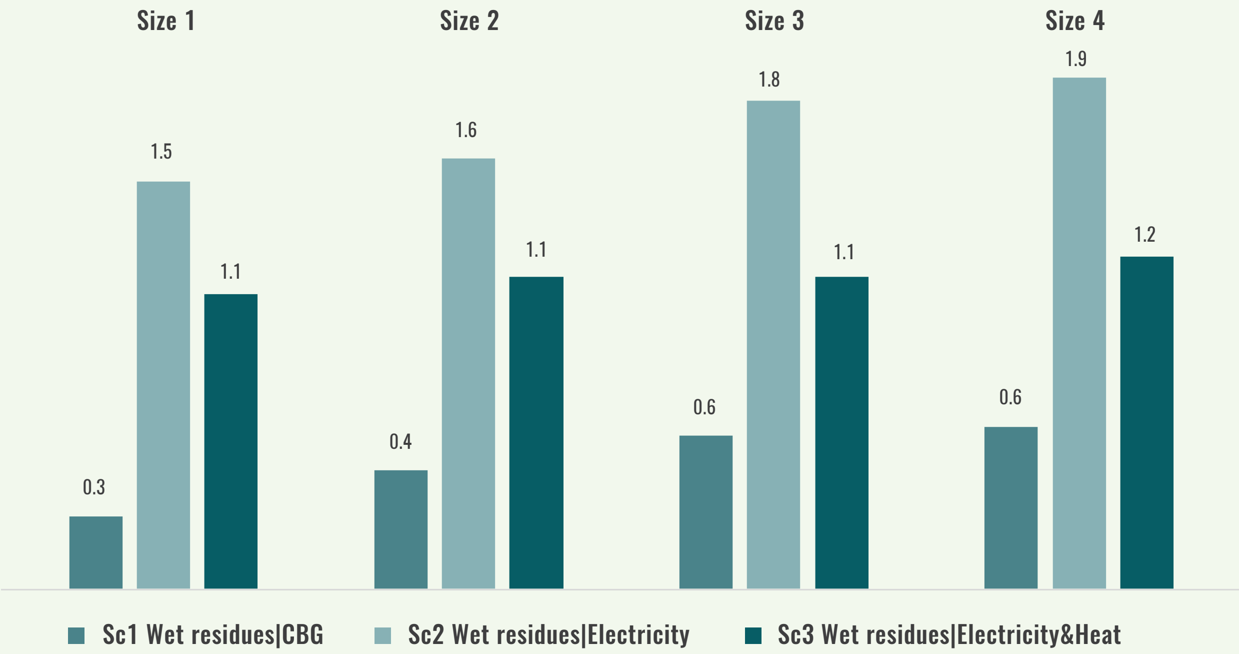
The effects mentioned for Scenario 1 are confirmed once the investment per customer index has been analysed. This index reveals how much money should be invested to bring energy to each customer supplied. Thus, for the most profitable scenarios, the investment amounted 1 000 to 3 000 USD/customer. In the case of CBG production and transportation to customers, this value could reach more than 130 000 USD per customer.

The net emissions savings per US dollars invested measure how effectively the capital invested yields GHG emission savings. In this case, at their respective scales the obtained values values are higher for an exclusive electricity generation (scenario 2). This fact can be explained by the effect that feedstock procurement has on emissions where wet residues have an advantage because agricultural residues and wastes are valorized, and their emissions are avoided due to decomposition are mostly prevented. Thus, this effect continues to increase as long as the plant capacities increase.

Finally, **Table 24** summarizes the techno-economic performance for all scenarios. Based on the indicators described above and this Table, it was concluded that the best performance in terms of profit, number of potential beneficiaries, and GHG savings with reasonable capital investment needs was found for Scenarios 3. They could feasibly represent the most promising options for wet residues valorization to energy in the Seychelles.

FIGURE 64.

NET EMISSIONS SAVINGS PER USD INVESTED



Source: authors.

TABLE 24.

SUMMARY OF RESULTS FOR SCENARIOS 1 TO 3

SCENARIO ID	PROFIT PER USD INVESTED	CAPITAL INVESTMENT	NUMBER OF POTENTIAL BENEFICIARIES	GHG NET SAVINGS
SC1 BIOGAS|CNG	LOW	VERY HIGH	LOW	MEDIUM
SC2 BIOGAS|ELECTRICITY	HIGH	HIGH	MEDIUM	MEDIUM
SC3 BIOGAS|ELECTRICITY&HEAT	MEDIUM	MEDIUM	LOW	MEDIUM

4.4 CONTRIBUTION TO ELECTRICITY GENERATION AND GHG EMISSION SAVINGS REDUCTION TARGETS

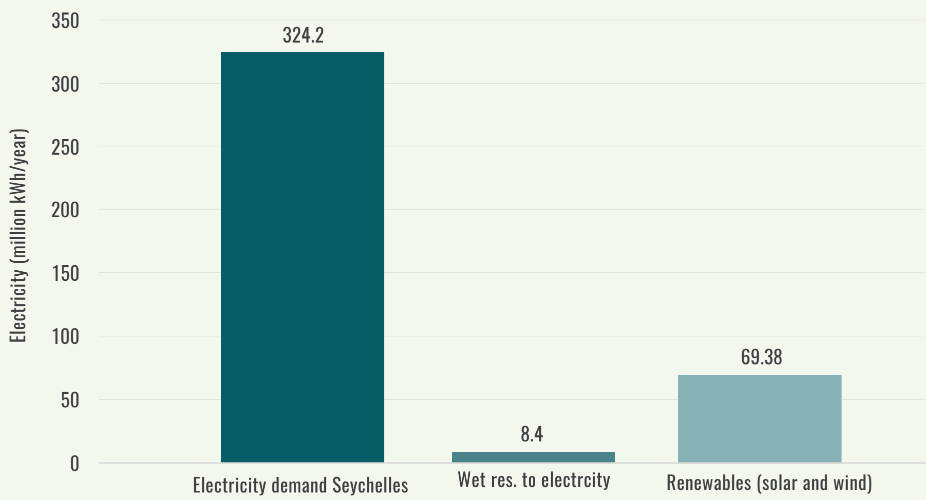
Based on the analyses described in the previous sections, it was concluded that in the case of residues the best overall performance would be obtained by using Scenario 2. Therefore, in this sub-section the BEFS assessment presents the potential contribution to renewable electricity targets and GHG emissions reductions.

In 2016, the Seychelles established a plan aiming to reach a '100 percent renewable Seychelles' based on a roadmap proposal presented by the MEECC, which was subsequently adopted and approved by the Cabinet of Ministers in April 2016 (Government of Seychelles, 2016b). The potential contribution of selected scenario responding to an electricity demand of 324.2 million kWh/year (SEC, 2017) is presented in **Figure 65**. In sum, the potential electricity generation (8.4 million kWh/yr) would contribute 2.6 percent towards the 100 percent renewable energy target.

FIGURE 65.

POTENTIAL CONTRIBUTION OF SELECTED ELECTRICITY GENERATION SCENARIOS

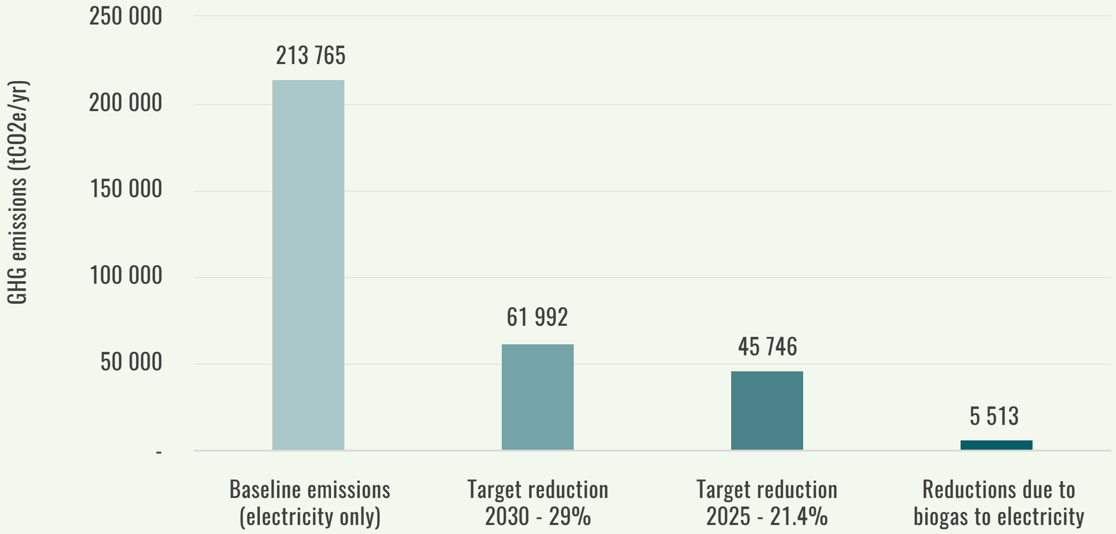
Source: authors.



Under the United Nations Framework Convention On Climate Change (UNFCCC) accepted by the Seychelles (Government of Seychelles, 2015), "The Republic of Seychelles will reduce its economy-wide absolute GHG emissions by 21.4 percent in 2025 and 29 percent in 2030 relative to baseline emissions." In terms of energy, the INDCs are focusing on making changes to public electricity (generation and demand-side management), land transport, and solid waste management. The emissions allocated to electricity generation in the Seychelles is 213 765 tCO_2e/year. Thus, specifically under these targets the target reduction allocated to public electricity will be 45 746 tCO_2e/year in 2025 and 61 992 tCO_2e/year in 2030. Therefore, the GHG savings contributions from the selected bioenergy alternatives reached 46 360 tCO_2e/year, which accounts for a 2.6 percent reduction compared to the baseline emissions (see *Figure 66*).

FIGURE 66.

CONTRIBUTION TO GHG EMISSION SAVINGS TARGETS



Source: authors.

4.5 CONCLUSIONS

Overall, the results obtained for bioenergy production in the Seychelles indicate that potentially available wet and dry residues could be considered sustainable options for bioenergy production, and contribute 2.6 percent towards a '100 percent renewable Seychelles target', as well as 2.6 percent to the emission reduction targets in electricity generation.

Among the three scenarios analysed for the bioenergy valorization of locally available residues and wastes in Mahé island, the assessment found that electricity cogeneration would be the most suitable technology to apply. As a result, Scenario 2 for wet residues was found to be the most promising pathway option, considering the potential profit, the number of potential consumers, and contribution to GHG savings reductions. Consequently, if the country chooses to build its largest plant capacities using all the biomass potential identified as available, it could potentially build a 1.45 MW plant based on wet residues. The combined investment to deploy this potential would reach 3 million US dollars and supply more than 2 000 households across Mahé island.

The potential locations of these cogeneration plants are constrained by the need to be within the proximity of the primary source of wet wastes, and water treatment plans, in order to reduce logistics costs.

The BEFS assessment considered the issues in terms of feedstock prices directly related to the logistics involved in their collection. However, this has been identified as the main bottleneck for bioenergy production profitability. The results indicated that the bioenergy plant would be able to pay a competitive price for the biomass collected, however, the biomass supply must be continuous and stable to avoid electricity generation interruptions. Consequently, the Seychellois government should consider developing a biomass residues supply chain that includes the participation of different actors and adequate policy support. The analysis has also shown the viability of including desalination plants for the provision of water to bioenergy plants. Furthermore, it was also proved that the bioenergy plants could supply the demands for heat and electricity in the desalination plants. Thus, the country would potentially be interested in expanding the capacities examined in this assessment, in order to establish larger desalination plants supplied with bioenergy to supplement the water supply in Mahé island.

CONCLUSIONS

The Republic of Seychelles, an Indian Ocean archipelago of 115 islands, is highly vulnerable to economic shocks and to climate change. A potential solution lies in sustainable bioenergy, from a variety of sources.

The Seychelles Energy Policy 2010-2030 (Government of Seychelles, 2010) calls for an end to the country's reliance on imported fossil fuels and advocates for more efficiency and sustainability: a target was set of 15 percent of energy to be from renewable sources by 2030. In 2016 the idea of '100 percent Renewable Seychelles' was adopted and approved by the Cabinet of Ministers (Government of Seychelles, 2016).

The government aims to reduce its economy-wide absolute GHG emissions by 122.5 ktCO_2e (just above 21 percent) in 2025 and an estimated 188 ktCO_2e in 2030 (equivalent to a 29 percent reduction) relative to baseline emissions (Government of Seychelles, 2015). However, mitigation strategies will have to be combined with adaptation strategies and measures to enable the Seychelles to cope with the impacts of climate change.

The assessment was conducted following the BEFS Approach of FAO (FAO, 2014b), and looked at different available bioenergy pathways.

The main objective of the biomass assessment was to determine the types of biomass that can serve as bioenergy feedstock. Based on the feedstock types identified, the biomass assessment analysis estimated the amount of feedstock produced and the amounts potentially available for bioenergy production, as well as their geographical distribution in the Seychelles when possible.

The assessment for the Seychelles covered production and availability and listed the issues that would need to be addressed in terms of feedstock accessibility. Moreover, potential negative environmental impacts of feedstock utilization were duly considered.

The analysis focused on primary crop residues, livestock residues (pig, chicken and cattle manure), forest feedstock (additional forest harvesting and forest harvesting residues) and biodegradable waste.

The commercial livestock sector in the Seychelles is dominated by large producers that are already collecting animal manure either for sale or for utilisation on the agricultural land. The assessment of livestock residues shows that the total manure available for biogas production amounts to 7 430 tonnes per year. The highest amount of available manure comes from pigs (56.7 percent), followed by chicken manure (39.4 percent).

The land in Seychelles is 90 percent covered by forests with about 50 percent of these located in protected areas (FAO, 2014). However, as a result of human activities, the forests have seriously deteriorated and have a high share of non-native species.

Sustainable forest management in the Seychelles is important for the provision of ecosystem services, rather than timber production. Therefore, only the additional harvesting of Albizia forest was considered for bioenergy production as this is an exotic species frequently considered to be a deterrent to forest management objectives. Assuming its utilisation at the level of a mean annual increment, the estimated potential on Mahé amounts to 20 000 m^3 per year. In addition to this, the potential of forest harvesting residues on plantations on Mahé was estimated at 1 073 m^3 per year.

There is limited arable land available in the country and a relatively small agricultural sector. Due to this, only banana residues were deemed available for bioenergy production. The total quantity of banana residues, including false trunk, leaves and peels, available for bioenergy amounts to 4 199 tonnes per year.

Waste management provides a further area of interest for bioenergy investment. Waste generation has been increasing due to economic development (the country has the highest per capita GDP in Africa) and tourism. Most of this waste ends up in landfill, despite the scarce space available (Meylan ***et al.***, 2018).

Around 70 000 tonnes of waste are delivered to the landfill on Mahé annually with the total biodegradable waste available for biogas production on Mahé estimated to be 36 743 tonnes per year.

These results are to be interpreted as an initial indication of feedstock availability for energy production and the amounts of feedstock that would be actually accessible need to be quantified with on the ground verification.

Based on the amount of biomass assessed as available, a technoeconomic analysis of energy options was carried out. The assessment incorporated a series of scenarios used to capture variations in prices, market set up and different production methods for the energy products, namely CBG, electricity, and heat. The analysis defined the unit production costs of each technology, the capital investment needs and the profitability under a set of comparison prices.

The assessment found that electricity cogeneration would be the most suitable technology to use.

As a result, Scenario 2 for wet residues was the most promising pathway option, considering the potential profit, the number of potential consumers, and contribution to GHG savings reductions.

According to this assessment, if the country chooses to build its largest feasible plant capacities using all the available biomass potential, it could build a 1.45 MW plant based on wet residues. The combined investment to deploy this potential would reach 3 million US dollars and supply more than 2 000 households across Mahé island.

Based on the '100 percent renewable Seychelles' aspiration, the potential contribution of the selected energy pathway is 8.4 million kWh/yr and would contribute 2.6 percent towards the 100 percent renewable energy target. Moreover, the GHG savings contributions from the selected bioenergy alternative would reach 46 360 tCO_2e/year, which accounts for a 2.6 percent reduction compared to baseline emissions.

The assessment considered the issues in terms of feedstock prices directly related to the logistics involved in their collection, an issue identified as the main bottleneck for bioenergy production profitability. The results indicated that the bioenergy plant would be able to pay a competitive price for the biomass collected; however, the supply must be continuous and stable to avoid electricity generation interruptions. Consequently, the development of a biomass residues supply chain would be required to successfully deploy bioenergy.

The analysis has also shown the viability of incorporating the use of sustainable bioenergy with desalination plants, and thus expanding the use of this technology to supplement freshwater supplies.

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A sustainable and stable energy supply is essential for a country's stability and wellbeing. Seychelles, like many Small Island Developing States (SIDS), currently depends on imported energy, in the form of fossil fuels. The high dependence on fossil fuel imports means Seychelles is highly vulnerable to disruptions in global markets. The situation is exacerbated by a reliance on imported food, which accounts for about 70 percent of food consumption. To limit this dependence, it is aiming to increase its reliance on renewable energy to 15 percent by 2030, with a long-term ambition of using 100 percent renewable sources for electricity production.

Sustainable bioenergy is one form of renewable energy that can be used to green a country's energy mix. This Sustainable Bioenergy Assessment report for Seychelles looks at the potential for sustainable bioenergy within the country, considering the country context, conditions and delicate habitat. The report considers sustainable biomass sources from the agriculture, forestry and waste sectors.

The assessment was conducted following the Bioenergy and Food Security (BEFS) Approach of FAO, and identifies a number of bioenergy pathways relevant for the country. Within the report, the different forms of biomass, their availability and viability are assessed. Livestock, crop and forestry residues, and the biodegradable portion of waste, otherwise destined for landfill, are among the sources of biomass considered. The use of these biomass types and amounts are then assessed from a technical and economic point of view, under different price scenarios, for the production of energy.

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