Bioenergy for Sustainable Local Energy Services and Energy Access in Africa

Demand Sector Report 4: Palm Oil Processing
Focus Country: Ghana

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AIGUASOL

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Cover photo: Biogas plant at Ghana Oil Palm Development Company, Kwae. Credit: Alex Bulnes (2017)

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EXECUTIVE SUMMARY

NIRAS-LTS partnered with Aston University, E4tech and AIGUASOL to research the opportunities and constraints for bioenergy development in sub-Saharan Africa (SSA) across seven shortlisted industries, through five interlinked themes: biomass resources, technology, economic competitiveness, commercial viability and institutional, market and regulatory frameworks. This report, the fourth in the series, focuses on the bioenergy opportunities in the palm oil processing sector in Ghana.

Oil palm is an important commercial crop in Ghana. Large-scale processors, who account for 40% of oil output, have sufficient scale, financial capacity, energy demand and human resources to support investments in modern bioenergy technology. The six largest processors have installed combustion-based CHP plants to supply their own electricity and process heat. One company (GOPDC) also uses palm oil mill effluent (POME), an acidic processing by-product, as feedstock for an AD system to generate biogas, which supplies heat to its palm oil refining operation at Kwae in Ghana’s Eastern Region. AD also reduces the environmental risks of improper POME disposal and produces digestate with nutritional benefits for soils. The research explored the commercial opportunity for POME-based AD in Ghana’s palm oil industry.

Biomass resource assessments indicate that there is sufficient POME at Ghana’s largest processors to meet the potential heat demand if they wished to refine all their crude palm oil, though four of the six largest processors do not currently have refineries. Technology is not a constraint to wider adoption of AD among these industrial-scale processors. Suitable technology for POME-based AD has been fine-tuned in Latin America and SE Asia over the past 30 years. The leading technology providers offer integrated partnerships, custom-built designs and extended on-site training - vital to engender customer confidence in an immature African market.

Economic assessments indicate cost savings from replacing diesel with biogas to generate heat for palm oil refining. Despite this saving, wider adoption of AD is hampered by the fact that all the large processors already have combustion-based CHP systems for meeting their energy demands, and can also access cheap and abundant grid electricity. Other commercial motivations for AD, such as stronger environmental enforcement or digestate valorisation, are unlikely to strengthen the commercial case significantly, as there are less costly alternatives for effective POME management and the efficacy of AD digestate as a fertiliser is not fully established.

From a policy and regulatory perspective, an oversupply of electricity on Ghana’s grid, mostly from fossil fuel-based generation, has led to virtually no new renewable electricity capacity being licensed since 2018. This effectively prevents bioenergy development for electricity generation, except for self-consumption, and significantly constrains investment in power generation from oil palm residues by large processors. It is hoped that the new National Energy Plan, currently under legislative review, will break this bottleneck to encourage biomass-based electricity generation into the grid.

Overall, the wider adoption of AD is likely to be limited to those mills with a demand for process heat (e.g. for a refinery) that a CHP system alone cannot satisfy. Even here, it may prove more economically expedient to expand existing CHP systems, if sufficient solid oil palm residues are available.

CONTENTS

LIST OF ACRONYMS

ABEX	abandonment expenditure
AD	anaerobic digestion
BOD	biochemical oxygen demand
BOPP	Benso Oil Palm Plantation
BPA	BUI Power Authority
BSEAA	Bioenergy for Sustainable Local Energy Services and Energy Access in Africa
CAPEX	capital expenditure
CHP	combined heat and power
COD	chemical oxygen demand
CPO	crude palm oil
DAES	Directorate for Agricultural Extension Services
DCS	Directorate for Crop Services
ECG	Electricity Company of Ghana
EFB	empty fruit bunch
EPA	Environmental Protection Agency
FFB	fresh fruit bunch
FiT	Feed-in Tariff
G&I	Gender and Inclusion
GHS	Ghanaian Cedi
GOPDC	Ghana Oil Palm Development Company
GridCo	Ghana Grid Company
IPP	Independent Power Producer
JOM	Juaben Oil Mills
LCC	Life Cycle Cost
LCOE	Levelized Cost of Energy
MCA	multi-criteria analysis
MEB	Mass-energy balance
Mt	mega tonne (1 million tonnes)
NEDCo	Northern Electricity Distribution Company
OPEX	operational expenditure
PKS	palm kernel shell
POME	palm oil mill effluent
PPA	Power Purchase Agreement
PSG	Plantations SOCFINAF Ghana
RSPO	Roundtable on Sustainable Palm Oil
SSA	Sub-Saharan Africa
TEA	Transforming Energy Access
TOPP	Twifo Oil Palm Plantation
USD	United States Dollar

1 INTRODUCTION

NIRAS-LTS partnered with Aston University, E4tech and AIGUASOL to implement a 2-year project - 'Bioenergy for Sustainable Local Energy Services and Energy Access in Africa-Phase 2' (BSEAA2). BSEAA2 was part of the Transforming Energy Access (TEA) programme, which is funded with UK aid from the UK government. TEA is a research and innovation platform supporting the technologies, business models and skills needed to enable an inclusive clean energy transition. TEA works via partnerships to support emerging clean energy generation technologies, productive appliances, smart networks, energy storage and more. It increases access to clean, modern energy services for people and enterprises in sub-Saharan Africa (SSA) and South Asia, improving their lives, creating jobs and boosting green economic opportunities.

BSEAA2 was intended to identify and support the development of innovative, commercial bioenergy pathways and technologies to accelerate the adoption of bioenergy in SSA. Building upon BSEAA Phase 1, which took place in 2016/17, the second phase focused on opportunities for the development of anaerobic digestion (AD) and combustion for electricity and/or heat generation in the range 10 kW to 5 MW, with a Technology Readiness Level of 5+. That is, technologies that had been successfully piloted in a representative commercial setting.

The research team investigated the challenges and opportunities affecting the commercial deployment of these technologies in ten focus countries in SSA (Ethiopia, Ghana, Kenya, Mozambique, Nigeria, Rwanda, South Africa, Tanzania, Uganda and Zambia), investigated through six relevant themes: biomass resources, technology, economics, business models, institutional, market and regulatory frameworks, and gender and inclusion (G&I). The research targets bioenergy entrepreneurs, investors and policymakers, aiming to catalyse action for the further development of commercial bioenergy in SSA.

Commercial opportunities and constraints for bioenergy development were assessed within seven shortlisted industries, referred to as 'demand sectors'. These demand sectors and their associated bioenergy pathway and focus countries are presented in Table 1-1. This report, the fourth in the series, focuses on the bioenergy opportunity in the palm oil processing sector in Ghana.

Table 1-1. Shortlisted demand sectors for BSEAA2 research

No.	Demand sector	Biomass resource	Technology	Country
1	Cement manufacturing	Biomass residues, part-replacing fossil fuel	Combustion for heat	Nigeria
2	Tea processing	Biomass briquettes, part-replacing fuelwood		Kenya
3	Wood processing	Wood processing residues	Combustion for CHP	Tanzania
4	**Palm oil processing**	**Palm oil mill effluent**	**AD for CHP**	**Ghana**
5	Horticulture	Fruit & vegetable processing residues		Kenya
6	Dairy	Cattle manure		South Africa
7	Sisal processing	Sisal processing residues	AD for electricity	Kenya

2 METHODOLOGY

2.1 OVERALL METHODOLOGY

During a 6-month preliminary assessment (2019-20), the research team screened a range of bioenergy 'pathways' in SSA involving AD or combustion, comprising a specific biomass feedstock, conversion technology, end use and demand sector. The aim was to identify the most promising pathways for the adoption of bioenergy-based combustion or AD across the target countries, for which the existence of at least one operational venture could be verified. This resulted in the shortlisting of the seven priority demand sectors in five countries. During the following 12 months (2020-21), these demand sectors were investigated in detail across the five research themes, to explore the experiences of both adopters and non-adopters of bioenergy technology.

Information was gathered from site visits to representative commercial operations and from other stakeholders active in bioenergy in SSA, from published literature and from partners of the TEA Programme, UK Energy Catalyst and Innovate UK. A bibliography is in Appendix 1 and a list of people consulted is in Appendix 2.

For each Demand Sector, a 'Base Case' and a 'Bioenergy Case' were identified:

- The **Base Case** refers to the industry standard for energy use in the given demand sector in the target country; that is, the default heat, power or combined heat and power (CHP) solution used by a majority of similar businesses.
- The **Bioenergy Case** refers to a specific enterprise (or 'flagship project') that has transitioned to the use of bioenergy for heat and/or electricity generation in the target demand sector, using either combustion or AD.

The Base Case and Bioenergy Case for the palm oil sector are defined in Table 2.1.

Table 2.1: Base Case and Bioenergy Case for the palm oil sector

Base Case	Bioenergy Case
Oil palm processors using solid processing residues in combustion-based combined heat and power (CHP) plants to generate heat and electricity	Oil palm processors using AD to generate process heat from palm oil mill effluent, in addition to combustion-based CHP for heat and electricity **Flagship project: Ghana Oil Palm Development Company at Kwae, Ghana**

This report analyses the Bioenergy Case flagship project across the six study themes of biomass resources, technology, economics, commercial viability, governance frameworks and G&I to identify the factors that have enabled the adoption of sustainable bioenergy. The findings are compared with Base Case examples to identify the opportunities and constraints for other enterprises in the same demand sector to adopt similar solutions. Based on this analysis, the potential and requirements for wider adoption of the Bioenergy Case in the chosen demand sector are assessed, both for the target country and for the other BSEAA2 countries.

2.2 Institutional, market and regulatory framework assessment

The assessment of the institutional, market and regulatory framework for bioenergy in Ghana's palm oil sector was based upon extensive web-based reviews and interviews with government, private sector and NGO informants, supplemented by team members' extensive experience in bioenergy, palm oil and energy policy in the country. The team examined institutions, policies, regulations, markets and finance frameworks relevant to the palm oil sector, environmental protection and electricity governance. Interviews were conducted with representatives of the Environmental Protection Agency, the Energy Commission and the SEforAll Secretariat, on the government side, and with senior technical staff or plant managers of Benso Oil Palm Plantation, Juaben Oil Mills, Norpalm Ghana Ltd and Ghana Oil Palm Development Company (GOPDC). Additional information was obtained from site visits to GOPDC and Juaben.

2.3 Biomass resource assessment

The objective of the resource assessment was to determine resource availability, bioenergy potential, feedstock-technology interface and mass-energy balance (MEB) for the relevant feedstocks in each demand sector, in this case solid and liquid palm oil processing residues. Existing data on agriculture and agro processing were used, adopting biomass feedstock categories from FAO (2004) and IEA & FAO (2017). Country-specific resource potential was calculated based on the quantity of oil palm fresh fruit bunches (FFB), the residue-to-product ratio, the recoverable fraction and its bioenergy potential (see source data in Appendix 3). An MEB model was also developed, to simulate the energy system using validated performance and efficiency data. Based on the known feedstock inputs of the flagship project, the model quantifies expected material flows and outputs of heat and power under optimised performance conditions, allowing replication potential to be estimated based on the preceding assessment of the biomass resource.

2.4 Technology assessment

The objective of the technology assessment was to determine the technological implications of bioenergy use for heat and/or power production in each demand sector, in this case the palm oil sector in Ghana, based on technical considerations and practical experiences at the Bioenergy Case flagship project, which was the AD plant at GOPDC. The GOPDC operation has been widely profiled in the literature, being the only AD facility at a palm oil processor in Ghana. Exploring GOPDC's experiences from a technical perspective required interaction with company staff both remotely and through a site visit. The technology and its supply chain landscape were characterised, and the opportunities and requirements for replication linked to technology were assessed.

2.5 Economic competitiveness analysis

The objective of the economic competitiveness analysis was to compare energy costs under the Base Case and the Bioenergy Case, to investigate potential economic drivers for wider adoption of bioenergy in the demand sector in question. A 10-year discounted cash flow analysis was carried out using an Excel-based Life-Cycle Cost

(LCC) modelling toolkit developed by AIGUASOL (see Appendix 4).[1] The main economic indicator considered was the Levelized Cost of Energy (LCOE), in USD/MWh. LCOE comprises CAPEX (upfront investment and other amortizable costs), OPEX (personnel, consumables and operating costs) and ABEX (abandonment expenditures). LCOE was calculated for both heat and electricity. The model was also used to perform sensitivity analyses on LCOE, considering a range of values for relevant input parameters.

2.6 Commercial viability assessment

The objective of this assessment was to determine the commercial case for bioenergy use in each demand sector, the factors affecting its successful adoption at the flagship project and the potential for wider uptake in the same sector, based on barriers, enablers, market potential and finance. The Bioenergy Case at GOPDC was first analysed to identify the elements responsible for commercial success linked, for example, to supply chain ownership, demand for heat and electricity and other factors such as waste disposal and financing. Information about the operation was obtained from stakeholder interviews and literature review. This was followed by an analysis of the wider commercial potential in the palm oil sector, analysing the barriers and enablers for supplying both heat and power under various scenarios. Taken together with an assessment of market size and conditions, the barrier analysis gave an indication of wider market potential. Finally, potential sources of finance and their relevance for bioenergy projects such as this were assessed.

2.7 Gender and inclusion assessment

The objective of the gender and inclusion research was to identify G&I-related issues in each demand sector, and to highlight potential areas for improved awareness, inclusion and participation of women. The research framework was adapted from a UNDP (2004) toolkit, and was structured around: access to assets; beliefs and perceptions; practices and participation; and institutional laws and policies. The research focused mainly on the production and supply of feedstocks, and, where applicable, the bioenergy conversion process. A literature review was also carried out, and further information was gathered through interviews with informants working in G&I and at the flagship project.

2.8 Multi-Criteria analysis

A multi-criteria analysis (MCA) was carried out to summarise the degree to which each the study's five thematic strands are conducive or detrimental to the adoption of the particular bioenergy solution in each demand sector. Each theme was given an average 'score' from 1 to 10, based on the degree to which various sub-factors under each theme make a positive contribution (high score) or act as an impediment (low score) to the viability of the Bioenergy Case. The MCA results are presented in the report's concluding chapter as a multi-point spider diagram, to provide a graphical summary of the factors most likely to support or impede successful adoption of bioenergy in the demand sector in question. The input data for the MCA are in Appendix 5.

[1] 10 years is a standardised period chosen for economic analysis based on an averaging of longer periods generally applicable for sustainability assessments and shorter periods applicable for investors consideration, and is not necessarily indicative of the functional lifetime of a particular project.

3 OVERVIEW OF PALM OIL SECTOR

3.1 SECTOR LANDSCAPE

Agriculture dominates Ghana's economy and accounts for 54% of GDP, 40% of export income and 52% of labour force employment or engagement (FAO, 2020). The majority of farms are very small and only 15% are above 2 ha (ibid.)

The main agricultural crops by weight are roots and tubers, which make up over three quarters of total production, dominated by cassava (see Figure 3-1). In the southwest of the country, tree crops such as cocoa, oil palm, coffee and rubber are dominant.

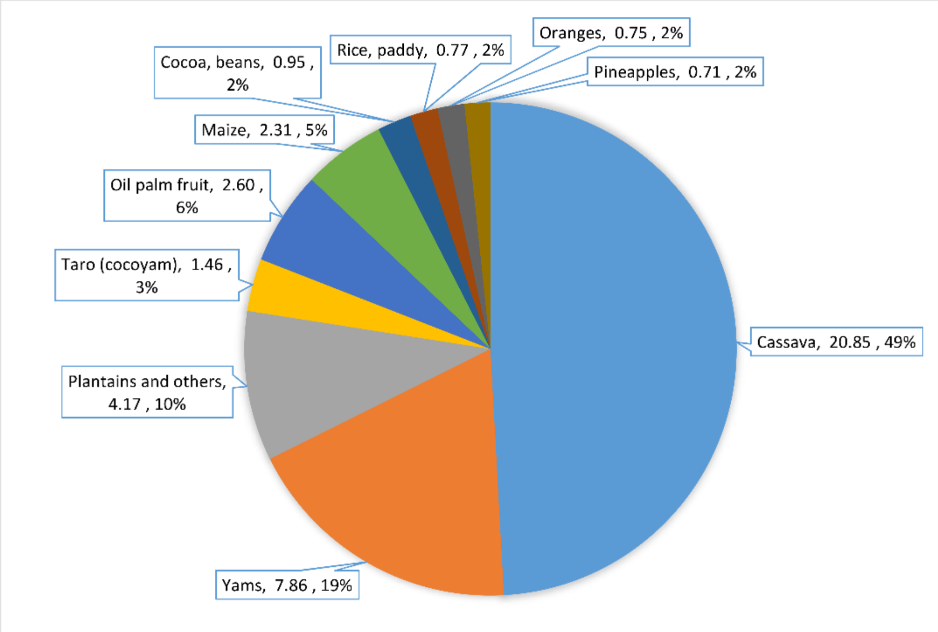


Figure 3-1. Top 10 crops in Ghana (Mt/yr and percentages) (FAO, 2020)

Palm oil is Ghana's most important non-starch crop and edible oil. Ghana produces about 2.6 million tonnes (Mt) of oil palm FFB per annum, grown on ~370,000 ha, from which 312,530 t of palm oil is extracted (FAO, 2020). 88% of the oil palm area is under smallholder management and the balance under large estates with on-site processing mills, but smallholders only account for about 60% of oil output as their average productivity is lower (Osei-Amponsah et al., 2012; Preferred by Nature, n.d.).

The vast majority (70%) of smallholders are independent private farmers, harvesting from wild palm groves or scattered trees, and selling their fruits on the open market (Ofosu-Budu & Sarpong, 2013). A further 28% are out-growers for large estates, where they are sufficiently close (<50 km) for the economic delivery of FFB (Osei-Amponsah et al., 2012). These out-growers are often given extension advice, agricultural inputs and other support, especially when partnered with estates that have Roundtable on Sustainable Palm Oil (RSPO) certification (Khatun et al., 2020; Moncoquet & Ros-Tonen, 2019). Small-scale producers, on the other hand, are not covered by certification schemes, as they lack the means to demonstrate compliance and have limited opportunities to influence the certification criteria (ibid.). The balance of 2% of smallholders operate on land that belongs to the larger estates.

3.2 BIOENERGY IN THE PALM OIL SECTOR

The processing of FFB generates large quantities of solid residues, mainly empty fruit bunches (EFB), fruit fibre and palm kernel shell (PKS), as well as liquid residues in the form of palm oil mill effluent (POME).

The small-scale processors who dominate Ghana's palm oil sector use manual techniques characterized by low extraction rates. Drums, pots or vats are used for cooking the palm fruits and processing the oil over open fires, fuelled with EFB, PKS and fruit fibres (Ministry of Energy, 2019). There is little motivation for such processors to adopt modern bioenergy technology for heat or power production, due to insufficient feedstock beyond that required for process heat, lack of demand for additional energy, the standardisation of boilers designed for >10 t/hr processing capacity (with customisation for smaller sizes prohibitively expensive), lack of capital and a lack of skilled labour to operate and maintain more sophisticated systems.

It is therefore only the country's largest processors that have sufficient throughput, financial capacity, energy demand and human resources to justify investments in modern bioenergy technology. These are GOPDC, Plantations SOCFINAF Ghana (PSG), Twifo Oil Palm Plantation (TOPP), Norpalm Ghana, Benso Oil Palm Plantation (BOPP) and Juaben Oil Mills (JOM). See location map in Figure 3-2 below.

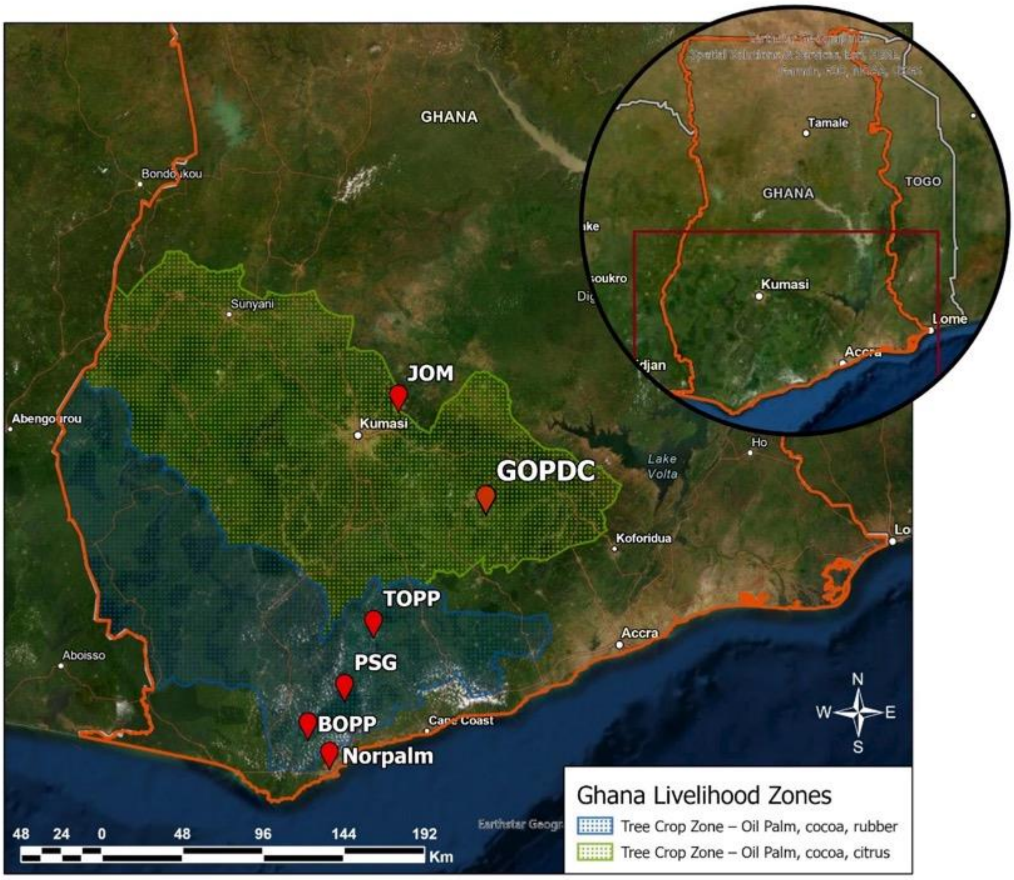


Figure 3-2. Map showing location of Ghana's oil palm belt and largest oil palm processors (Source: authors' compilation)

The six largest processors have combustion-based CHP plants at their mills that use solid oil palm residues for generating electricity for their own factory operations, administrative functions and staff housing, as well as low pressure steam to supply process heat for the various stages of oil extraction. The remainder of their power requirements are met through a combination of grid electricity and back-up diesel generators. Combustion-based CHP systems are a straightforward and economically viable solution for these larger mills to generate power – and especially heat - and therefore form the industry standard 'Base Case' for this analysis.

Palm oil processing also generates polluting liquid waste in the form of POME. Raw POME contains 90-95% water and includes residual oil, soil particles and suspended solids. POME is acidic (pH 4 to 5) and has high biochemical oxygen demand (BOD) and chemical oxygen demand (COD) of 25,000 and 50,000 mg/l, respectively (Kamyab et al., 2018), introducing a high risk of aquatic contamination. The industry norm at Ghana's large mills is for POME to be discharged to aerobic treatment ponds for 90 to 120 days and then used for irrigation. This approach releases methane into the atmosphere and risks the leaching of contaminants into soil and groundwater.

Much research has been dedicated to alleviating the environmental threat posed by POME disposal, and AD is one solution that can reduce this threat, while simultaneously producing heat and/or power, plus benign liquid digestate with nutritional benefits for soils. GOPDC uses the POME as the primary fuel for an AD system to generate biogas to supply heat to its oil refining operation, which represents the Bioenergy Case for this demand sector. This research explores the commercial opportunity for further adoption of POME-based AD for bioenergy in the palm oil industry in Ghana.

3.3 Institutional, regulatory and finance framework

3.3.1 Institutional framework

Ghana has an extensive and well-coordinated framework for renewable energy regulation, support and financing, with ambitious targets for investment in electricity generation from renewable sources in the Ghana Renewable Energy Masterplan (Ministry of Energy, 2019).

The institutional framework for **electricity** is illustrated in Figure 3-3. The Ministry of Energy is responsible for formulating, implementing, monitoring and evaluating policies, programmes and projects in the electricity sector. All sector entities are overseen and regulated by the Energy Commission of Ghana, under the Energy Commission Act (Republic of Ghana, 1997a) which is responsible for the licensing of renewable energy operators and setting technical standards for their performance, as well as sector planning and policy advice. The Ghana Grid Company (GridCo) was established in 2006 as effectively a national monopoly that transmits electricity to the Electricity Company of Ghana (ECG), the Northern Electricity Distribution Company (NEDCo), Enclave Power, the mines and parts of the Volta River Authority. The ECG and NEDCo are effectively Ghana's primary distribution entities. The Public Utilities Regulatory Commission, created by the Public Utilities Regulatory Commission Act (Republic of Ghana, 1997b), is the primary electricity regulator and oversees the Volta

River Authority, Bui Power Authority (BPA) (Republic of Ghana, 2007)[2], NEDCo, GridCo and the ECG.

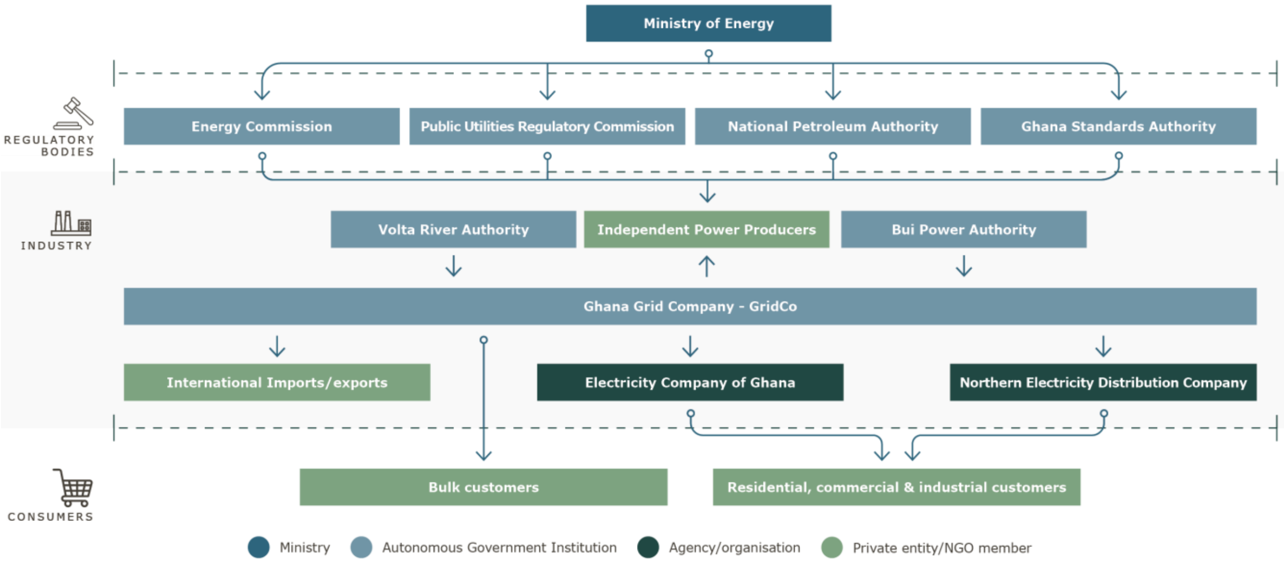


Figure 3-3. Institutional framework for electricity in Ghana (Source: authors' compilation)

On the **agriculture** side, the key institutions responsible for palm oil production and refining are shown in Figure 3-4. Palm oil production is supported and managed by the Ministry of Food and Agriculture, primarily through its Directorate for Agricultural Extension Services (DAES) and Directorate for Crop Services (DCS) within the framework of Ghana's Oil Palm Masterplan (Ministry of Agriculture, 2019). The DAES, together with the DCS's Tree & Industrial Crops Unit, works through regional and district Agriculture Development Units to support oil palm growers and producers to improve their stock and silviculture practices.

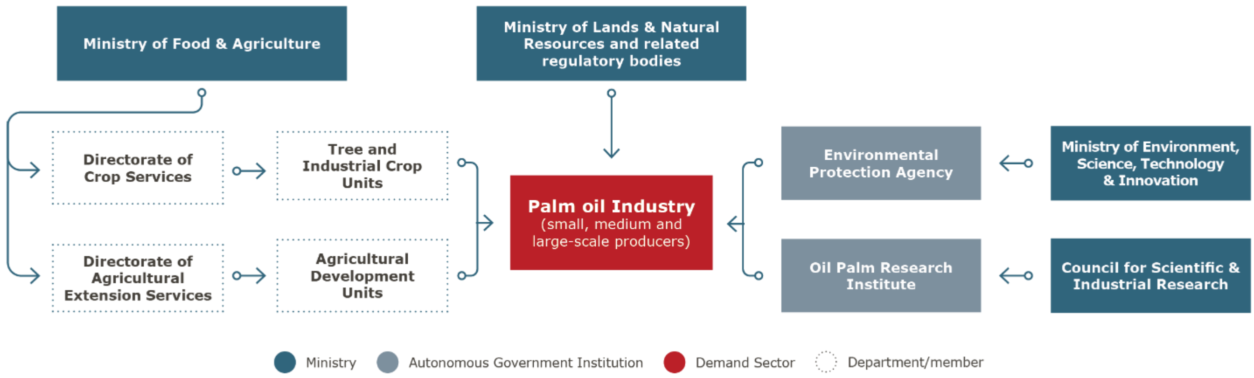


Figure 3-4. Institutional framework for the palm oil sector in Ghana (Source: authors' compilation)

Ghana's Environmental Protection Agency (EPA), under the Ministry of Environment, Science, Technology and Innovation, regulates environmental aspects of the industry through the issuance of Environmental Permits. The Oil Palm Research Institute, one of the 13 institutes of Ghana's Council for Scientific and Industrial Research, offers

[2] The BPA was established as a special agency with a mandate to plan, execute and manage the 40 MW Bui Hydroelectric Project, now the Bui Generating Station, and work with communities in the Bui catchment to develop social and economic services from the revenues generated by the station.

technical support to the industry, including developing technologies for sustainable production of palm oil, efficient exploitation of palm kernels (e.g. for energy production) and the safe and productive management of other processing wastes.

The Ministry of Lands and Natural Resources, the Lands Commission, traditional authorities, the Administrator of Stool Lands, and town and country planning authorities are the main institutions responsible for land on which oil palm is grown. Other relevant authorities include the Registrar General's Department, metropolitan, municipal and district assemblies, traditional authorities, the Food and Drugs Authority, the Water Resources Commission and the Plant Protection and Regulatory Services Directorate.

3.3.2 Policy and regulations

Electricity policy and regulations: Ghana has an ambitious National Energy Policy (Ministry of Energy, 2010) and Renewable Energy Act (Republic of Ghana, 2011), with a target of increasing the proportion of renewable energy in the national electricity generation mix from 42.5 MW in 2015 to about 1,364 MW (1,095 MW of grid connection and the rest off-grid) by 2030, as per the national Renewable Energy Masterplan (Ministry of Energy, 2019). Major droughts significantly reduced hydroelectricity generation in the early 2010s. Accompanied by lower performance from aging thermal plants, this prompted government to authorise significant investment in fossil fuel generation to meet the shortfall, leading to an over-supply of nearly twice Ghana's electricity generation capacity relative to demand, which continues today.

This over-supply from fossil fuels curtailed support for renewable energy, to the extent that permits and licences for new renewable energy plants to sell electricity to the grid have been suspended by the Energy Commission (the regulator) since 2018. This is a major obstacle to the development of bioenergy for electricity generation, including investments in the oil palm sector that might include sale of surplus electricity to the grid. It is hoped that the new National Energy Plan, currently under legislative review, will break this bottleneck to encourage bioelectricity generation into the grid in the near future, particularly in areas of weak grid supply.

Environmental policy and regulations: It is relevant to highlight policies and regulations on environmental management and waste disposal, given the focus in this study on producing bioenergy using POME, which is highly polluting if not properly treated. The EPA Act – Act 490 (Republic of Ghana, 1994) established the Environmental Protection Agency. This was followed by the Environmental Assessment Regulations (Ghana EPA, 1999) which requires oil palm processors to undertake environmental impact assessments and obtain EPA permits for dealing with wastes, particularly POME. Other applicable environmental regulations include the Water Resources Commission Act (Republic of Ghana, 1996), Water Use Regulation (Water Resources Commission, 2001) and Land Planning and Soil Conservation (Amendment) Act (Republic of Ghana, 1957). The Hazardous and Electronic Waste Control and Management Act 917 (Ghana EPA, 2016) also applies to POME management in the palm oil industries.

3.3.3 Finance

Ghana has one of the most open and active financial sectors in Africa. A number of local banks lend for capital-intensive development projects such as bioenergy investments by palm oil factories. The most active financing institutions in the oil palm sector include the Agricultural Development Bank of Ghana, National Investment Bank and First National Bank of Ghana. International banks with local representation include Absa, Standard Chartered, Stanbic and Société Générale Ghana, together with regional development banks such as the African Development Bank, the Banque Ouest Africaine de Développement and the ECOWAS Bank for Investment and Development. Bilateral international development finance institutions operating in Ghana include the UK's CDC Group, UK Export Finance. Germany's KfW, France's AFD, FMO Netherlands and the US Overseas Private Development Corporation, all active in renewable energy finance. International multilateral financial institutions active in Ghana include the European Investment Bank, the World Bank and the International Finance Corporation.

4 OVERVIEW OF BIOENERGY CASE

4.1 PROJECT SUMMARY

GOPDC is a large agro-industrial enterprise specializing in the cultivation of oil palm and the extraction of crude palm oil and palm kernel oil. GOPDC is wholly owned by *Société d'Investissement pour l'Agriculture Tropicale* (Siat Group) of Belgium. Siat has additional shareholdings in two palm oil estates in Nigeria.

GOPDC is Ghana's largest palm oil company and owns two industrial plantations at Kwae and Okumaning in Eastern Region, where it manages approximately 8,000 ha of oil palm on its own estates and supports 7,000 out-growers to cultivate an additional 13,700 ha. At its main processing plant at Kwae, the company runs a 60 t/hr FFB palm oil mill, a 60 t/day palm kernel mill, a 2 t/hr palm kernel cake pellet plant and a 100 t/day refinery and fractionation plant (GOPDC, 2020). The refinery is one of only two that exist in Ghana, the other being at Juaben Oil Mills in Ashanti Region.

GOPDC processed 138,184 t of FFB in 2019, of which the company's own estates supplied about 110,000 t and the balance came from out-growers and other suppliers. Solid residues from the mill are used to fuel a combustion-based CHP plant, while the POME is fed to an AD plant for steam production (see layout in Figure 4-1). The two systems are operated largely independently and meet separate energy demands.[3]

The CHP plant will be described only briefly, as this is the standard technology adopted at Ghana's six largest oil palm processors. The AD plant will be analysed in more depth, this being the 'Bioenergy Case' that is unique to GOPDC. The technical information below was kindly provided by GOPDC technical staff and a site visit, except where otherwise referenced. Photos are provided in Appendix 6.

[3] The estimated energy demands of the mill are 19,947 MW_{th} (all from the combustion-based CHP system) and 12.04 GWh_e (of which 3.52 GWh_e comes from the CHP plant and the balance from the grid and diesel gensets). An additional heat requirement of 14,470 MWh_{th} for oil refining operations comes from a combination of biogas and diesel. See 4.4 below for details.

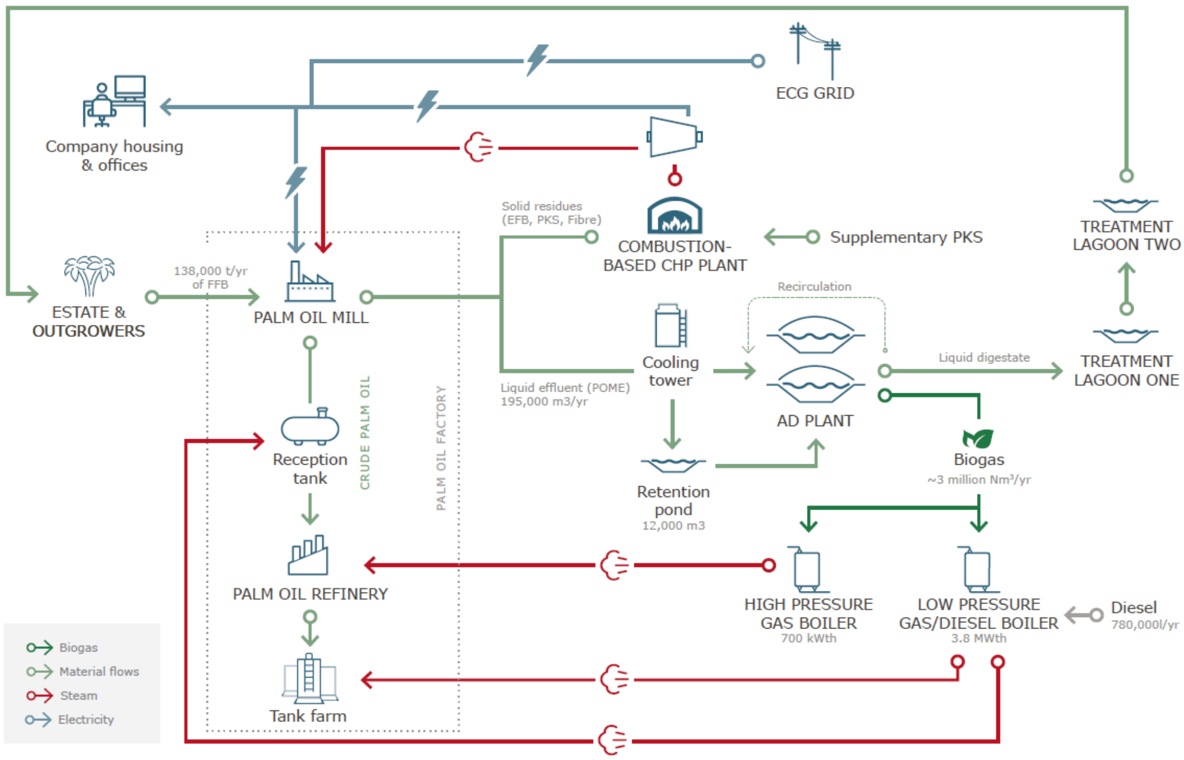


Figure 4-1. Schematic diagram of GOPDC energy system, including AD plant (Source: authors' compilation)

4.2 Technical details – combustion-based CHP plant

When the GOPDC mill at Kwae was opened in 1982, it had no grid electricity connection and the company installed two biomass boilers and a 615 kVA steam turbine to generate its own power. A third boiler was added in 1987, with a second turbine of 550 kVA. In order to handle the growing processing capacity of the mill, the demands of a new refinery and the rising costs of electricity and fossil fuels, the system was replaced in 2008/09 with a 30 t/h Vyncke boiler and a 2.5 MW Dresser-Rand turbine, and in 2015 with an additional 30 t/h Vickers boiler with a 1.5 MW Turbokraft turbine.[4] This CHP system generates electricity for internal use and low-pressure steam (up to 3.5 bar) for sterilising incoming FFB and providing heat to the oil pressing and clarification plants. GOPDC also has a 1,650 kVA standby genset, plus a smaller 469 kVA genset that provides power to the management quarters when the ECG cannot supply reliable grid power.

The CHP boilers are fuelled with PKS, fruit fibre and shredded EFB, in a preferred ratio of 30% shells to 70% fibre/EFB. As GOPDC doesn't generate sufficient PKS to maintain an optimal blend, additional shell is purchased from smaller milling companies and the informal sector.

GOPDC's in-house engineering team carries out most of the maintenance and repairs on the boilers, including refractory works, servicing, changing grate bars, fixing leaks in steam tubes and changing instruments. Vyncke and Vickers are contacted occasionally for guidance. External maintenance of the turbines (such as welding works or changing instruments) is also carried out by GOPDC staff, sometimes under

[4] The original boilers were scrapped as they were rated at 17 bar, whereas the new turbines required 25 bar.

the guidance of specialists from Siat Group sister companies, usually CHC Côte d'Ivoire.[5] Scheduled servicing that requires the turbines to be opened up is carried out by external specialists. The Dresser-Rand turbine is serviced by Siemens, while the Turbokraft turbine was originally serviced by the Malaysian manufacturer, but since 2018 has been serviced by Sociéte de Mécanique Générale (SOMEG) from Côte d'Ivoire, due to difficulties in securing a Turbokraft engineer.

The total power consumption of the Kwae complex was 12.04 GWh in 2019, falling slightly to 10.74 GWh in 2020 due to COVID-related impacts on production and marketing. The peak load is around 1.8 MW, of which the refinery and bottling operation account for ~20% and the residential areas ~15%. The 2.5 MW turbine could easily meet this peak load, so the 1.5 MW unit would usually be kept on stand-by. But the larger turbine has been offline for some time due, reportedly, to insufficient steam supply. Vyncke technicians have been trying to rectify the situation. The company has been fully reliant on the 1.5 MW turbine in the meantime. This is not large enough, which explains why the grid supplied 67.4% of all power in 2019 (with only 29.2% provided by the CHP plant and 3.4% from the gensets).

4.3 Technical details - AD plant

4.3.1 Technology and process

GOPDC generated 195,137 m^3 of POME in 2019, from the processing of 138,184 t of FFB. This equates to 1.4 m^3 of POME per tonne of FFB, which is rather high for reasons that are not clear, possibly resulting from the addition of wash water.

GOPDC has two adjacent balloon (lagoon) digesters for the production of biogas, each of 10,000 m^3 capacity. As the POME exits the milling plant, it is sent to a cooling tower for temperature reduction from ~60^{o}C to between 30 and 35^{o}C. It is then fed to the digesters, prioritising the unit with the lower gas pressure. About 50% of the digestate is recirculated via two pumping systems and mixed with the incoming effluent, to maintain the bacterial load within the substrate and ensure maximum gas productivity.

The biogas reactors operate in the mesophilic temperature range and require no heating (unlike similar systems at higher latitudes) and no mixing (as the recirculation achieves the same outcome). Compressors inject air to reduce H_2S build-up. Retention time averages 27 days during the peak processing season and 70 days during the rest of the year. CH_4 content was previously measured at 54 to 56%, although the gas analyser is now faulty. Pressure gauges are fitted on the balloons but are hard to reach, so pressure is estimated manually, often by walking on the balloons. Excess gas is occasionally flared.

A blower sends the biogas to two steam boilers, via inline water traps to remove moisture. The first is a 512-litre high pressure, closed circuit, vertical coil boiler manufactured by GekaKonus (Germany) in 2004, rated at 700 kW$_{th}$ using 1,834 kg/hr of steam at 95 bar maximum pressure (though operated at ~70 bar). The high-pressure steam is used for the refinery's deodorizer, which removes fatty acids from the crude palm oil (CPO) and changes the odour.

[5] www.siat-group.com/company-profile/chc-ivory-coast/

The second unit is a 3,200-litre dual-fuel gas/diesel horizontal boiler manufactured by Getabec (Germany) in 2005, which produces 5 t/hr of lower pressure steam at 12-12.5 bar (thus around 3.8 MW_{th}). This second boiler is co-fired with transport diesel when gas output is insufficient, and consumed 782,361 l of diesel in 2019. It is unclear why the company has chosen to use transport diesel rather than fuel oil, which would attract a lower rate of tax. The low-pressure steam is used for pre-warming the incoming CPO at a reception tank, and for keeping the finished product warm at the company's tank farm, for eventual pumping into tankers.

GOPDC had been discharging the reactor digestate into a series of three treatment ponds and then into a nearby river, but it now pumps out directly from the second pond for plantation irrigation. Research is ongoing to establish the agronomic benefits of this practice. The AD plant delivers average COD removal of 90% (Bulnes, 2017) and raises the substrate pH from 4.2 to 7.2, demonstrating massive impact on reducing the pollution potential of the POME.

4.3.2 System performance

From 1 m^3 of POME, the AD system is rated to deliver 23 m^3 of CH_4, 0.23 t of steam, 0.77 m^3 of treated effluent and 0.23 m^3 of biological sludge (Biotec International, 2020). Given that the system produced 3,023,924 normal cubic metres[6] (Nm^3) of biogas in 2019, from 195,137 m^3 of POME, productivity was ~33% lower, at 15.5 Nm^3 per m^3 of POME. The system's rated design capacity is 160,000 m^3/POME/yr and it was expected to produce 4 million Nm^3 of biogas per year (Bulnes, 2017), so despite feedstock input being above the system rating, gas output is 24% lower than expected. While the reasons for this are not known, there could perhaps be dilution of the POME with wash water or over-feeding of the reactors during the peak season, offset with under-feeding during the off-season.

The biogas displaced 910,012 litres of diesel that would otherwise have been required for the low-pressure boiler to generate steam for the refinery. The continued use of more than 782,000 l of diesel points to an opportunity to increase gas output for even higher diesel replacement. But the seasonality of POME production makes it challenging to achieve consistent year-round reactor performance, with a POME surplus for 5 months followed by a shortage for 7-months. Excess POME is stored in a 12,000 m^3 pond for later use, but this buffering is not sufficient to keep the system running at its full capacity for the whole year.

4.3.3 Technology supply

The entire AD plant was supplied and installed by Biotec International of Belgium, while the civil works were carried out by a Ghanaian contractor known as 2K Construction. Biotec is a leading provider of technology for biogas generation in tropical agro-industry. The company was founded in 1984 by the Conil family and now has subsidiaries in Colombia, Malaysia and Indonesia, and over 30 years' experience in wastewater and integrated organic matter management in tropical regions.[7]

Biotec is a specialist in POME treatment and valorisation: it built the second POME biodigester in the world (in 1988) and installed the first lagoon-based biodigester for

[6] A normal cubic metre is a standardised measure that would be the volume occupied by the gas under 'normal' conditions, i.e. 0°C and 1 atmosphere pressure (101.3 kPa).
[7] www.bio-tec.net

POME (in 1999). It has now designed and built 28 AD plants for POME, mostly in the 1-3 MW range, of which 50% are in Latin America and three are in West Africa.[8] In 2018, the GOPDC and Presco (Nigeria) plants earned Siat an award for 'Best International Agricultural Plant' from the World Biogas Association.[9] Biotec has also carried out an AD feasibility study for Norpalm Ghana Ltd. In addition to supplying AD system for large agro-industrial projects, Biotec has a joint venture with Sauter Biogas (Germany) for renewable natural gas generation from biomass in tropical countries,[10] a consultancy for organic effluent and residue valorisation and a social foundation in Colombia for household and community biodigesters.[11]

4.3.4 Operation and maintenance

While some companies use intermediaries and brokers to design and manage AD projects, for which they supply specialist components, Biotec prides itself on close customer engagement and provides a turnkey package of design, construction, training, monitoring and maintenance. The GOPDC plant was installed over 6 months from August 2014, and Biotec placed its own staff on-site for one year to train the local team. The cost of the plant was reportedly EUR 4.5m, with an expected payback period of 11 years (Ministry of Energy, 2019).

The plant has two managers and five workers per 8-hour shift, plus five office staff and one technical supervisor (who also oversees the CHP system, powerhouse, water treatment plant and other installations). System parameters are monitored via a Supervisory Control and Data Acquisition (SCADA) system, to which Biotec has remote access. Operation and maintenance involves continuous monitoring and daily system checks, with special attention paid to the microbiology of the digesters to optimise the fermentation process. The AD plant has 16 pumps and motors, which need rewinding as per their service schedules. There is minimal AD-specific expertise in Ghana, hence the lengthy in-house training provided by the manufacturer as part of the installation contract.

The GOPDC plant appears to be operating well under the control of a qualified and (now) experienced in-house team. The wide seasonal fluctuations in POME supply make it difficult to sustain consistent year-round performance, however, meaning that diesel must still be purchased to make up an energy shortfall to sustain a continuous supply of steam for the oil refinery's reception tank and tank farm.

4.4 Economic assessment

Table 4.1 summarises the data used in the LCC model for the GOPDC AD plant, as the Bioenergy Case, comparing it with a Base Case scenario of generating refinery heat using diesel-only boilers.

[A] At GOPDC in Ghana, the Siat-owned Presco mill in Nigeria and a former Siat-owned mill at Makouké in Gabon.
[9] www.presco-plc.com/latest-news/siat-wins-biogas-industry-award-for-best-agricultural-plant/
[10] www.agrogaz.com
[11] www.pro-organica.org

Table 4.1: Key project data for economic modelling

Category	Parameter	Value
General parameters	Discount rate	10%
	General growth rate	4.0% (Consumer Price Index)
	Electricity retail price	GHS 0.8436/kWh (USD 162.43/MWh) (as reported by GOPDC)
	Currency exchange rate	5.19 GHS/USD (3-yr average)
Base Case	Fuel for combustion-based CHP	EFB, PKS, fruit fibre. LHV 19.45 GJ/t
	Estimated cost of fuel for CHP	88% from own processing (nil cost) plus estimated 1,000 t/yr of PKS (~18% of fuel usage) purchased @ GHS 125/t
	Fuel for refinery boiler	Transport diesel. LHV 36 MJ/l. Cost USD 0.95/l
	Diesel consumption for refinery boiler	1,692,361 l/yr
	Nominal power	CHP unit: 1.5 MW_e, 12% electric eff., 68% thermal eff. Boilers (for CHP & refinery): ~14 MW_{th}, 85.5% eff.
	Capacity factor	52% (4,520 operating hrs/yr)
	Heat demand	14,470 MWh_{th}/yr (refinery, supplied from diesel boiler) 19,947 MWh_{th}/yr (mill, supplied from CHP unit)
	Electricity sources	CHP plant 29.2% (3.52 GWh/yr) Grid 67.4% (8.11 GWh/yr) Gensets 3.4% (0.41 GWh/yr)
Bioenergy Case	CAPEX	EUR 4.5 M (USD 5.5M) for AD plant + additional biogas boiler
	OPEX reduction	Savings of 910,000 l/yr of diesel for 140,000 t of FFB processed, with slight increase in operating costs
	Biogas yield	15.5 Nm^3/m^3 of POME (55% methane)
	POME disposal cost	0 USD/m^3
	POME treatment cost	0 USD/m^3 (various values modelled later in sensitivity analysis)
	Additional electricity demand (AD plant)	0.264 GWh/year (source: GOPDC Field visit)

Applying these input parameters, the LCC model shows that the GOPDC plant has slightly lower LCOE for both electricity and heat under the Bioenergy Case than the Base Case (Figure 4-2), in which the POME-fed AD plant has been installed to supplement the existing combustion-based CHP plant. A reduction of 6% is observed in the $LCOE_{heat}$ (from USD 64.6/MWh to USD 60.6/MWh).

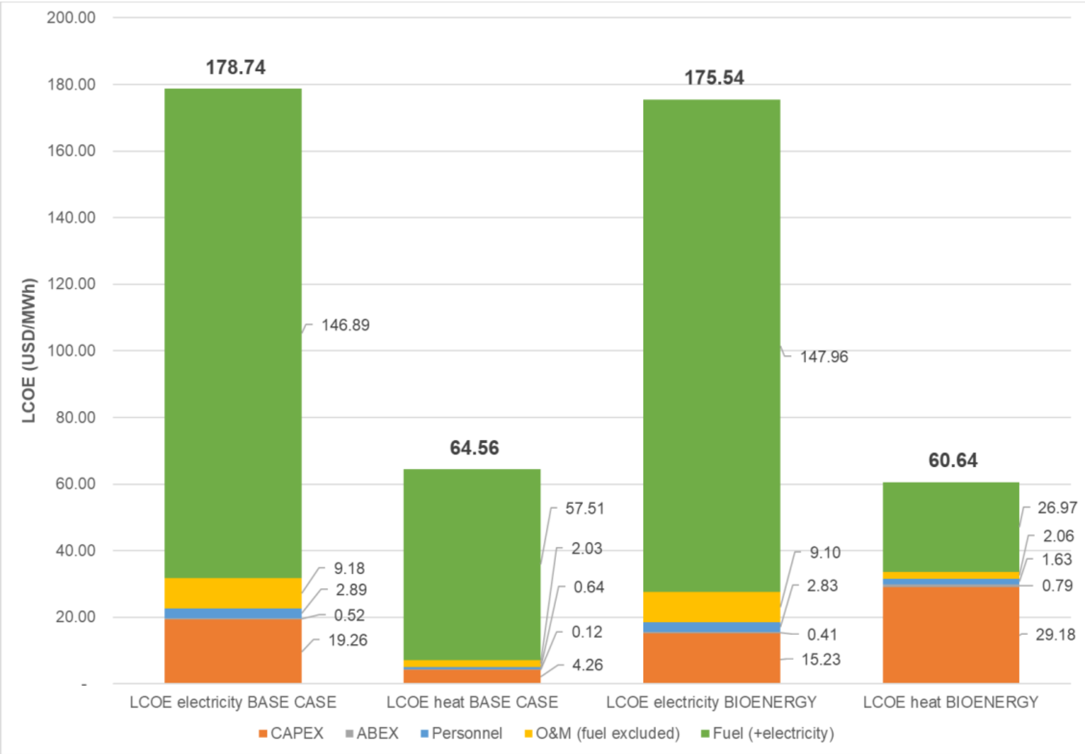


Figure 4-2: LCOE comparison for power and heat, Base Case vs. Bioenergy Case

The introduction of the AD plant results in a change to the $LCOE_{heat}$ breakdown, with higher contribution from CAPEX and lower share of OPEX. This would result in lower overall LCOE values if a longer evaluation period was considered beyond the 10 years modelled. For example, Figure 4-3 shows the impact of extending the period of analysis to 20 years, which produces a reduction in LCOE for heat of about 21% compared with the Base Case.

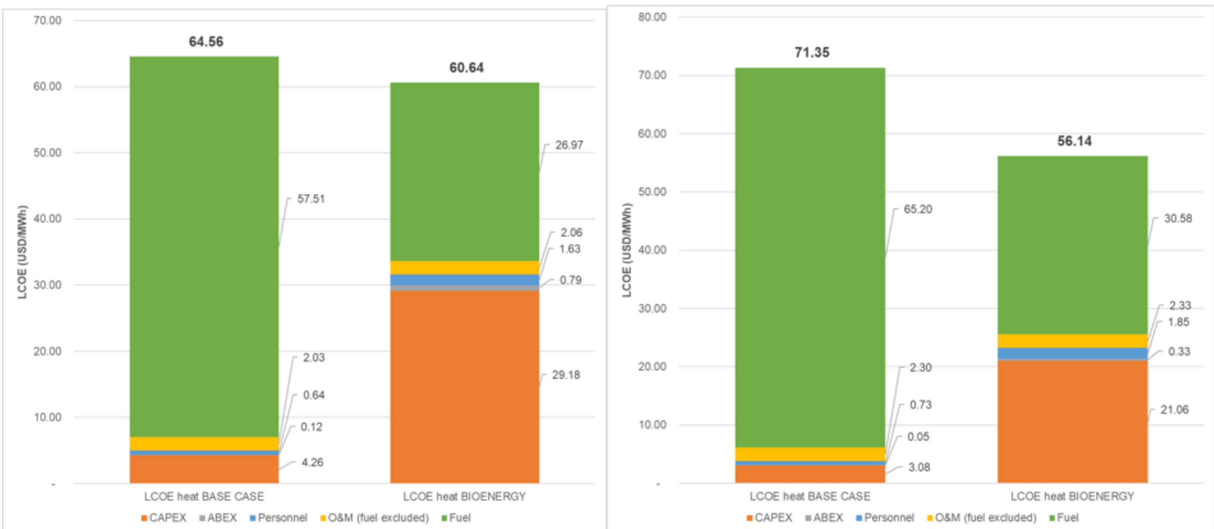


Figure 4-3: LCOE comparison for heat, Base Case vs. Bioenergy Case over 10 years (L) and 20 years (R)

Savings on aerobic POME treatment and benefits from upgraded digestate for soil improvement have not been considered in this economic analysis, but are investigated in the sensitivity analysis in section 5.3 below.

4.5 Commercial success factors

Figure 4-4 provides details of the ownership of the different stages of the supply chain for the Bioenergy Case at GOPDC.

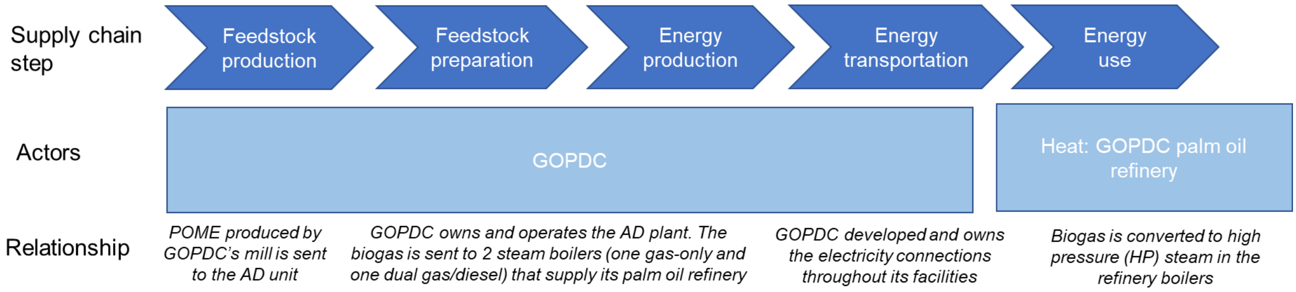


Figure 4-4: Overview of the GOPDC supply chain

GOPDC requires significantly more heat for its refinery than its CHP plant alone could generate. This need for supplementary process heat, together with a requirement to comply with environmental regulations concerning the disposal of POME, are likely to have been the main drivers for the company's investment in AD. Unlike similar investments seen in other industries and in other countries, demand for electricity was not a motivating factor for GOPDC, due to cheap and abundant grid supply, the availability of power from its combustion-based CHP plant, existing back-up generators and the absence of a market for surplus electricity due to excess power on the grid. The use of POME digestate as liquid fertilizer adds an important additional benefit stream, though this has not yet been valorised.

The success of the business model for the flagship AD project at GOPDC therefore depends predominantly on demand-side success factors relating to internal heat demand and the need for environmentally-compliant POME disposal, as well as GOPDC's ability to secure finance:

- **Heat demand for self-consumption:** GOPDC's oil refinery represents a significant source of captive demand for heat, in the form of high-pressure steam for the deodorising process and low-pressure steam for the reception tank and tank farm. The existing CHP plant could not meet this demand, so the additional heat is being generated using biogas.
- **Environmentally-compliant POME disposal:** As an RSPO-certified supplier and a socially responsible company, GOPDC has a strong interest in environmental accountability, both to comply with Ghanaian law and to demonstrate sustainable operating practices. Improving its production processes by using its own by-products and effluents to produce energy is an ideal opportunity to reach this goal (GIZ, 2014). GOPDC's former Biogas Manager highlighted the reputational benefits to GOPDC and the Siat Group of converting potentially polluting wastes to renewable energy (Bulnes, 2017).
- **Ability to secure finance:** Initially there were plans to secure funding for the AD plant through the Clean Development Mechanisms under the UNFCCC, presumably on the basis of avoided methane emissions from aerobic POME treatment and the use of diesel for steam production. This did not materialise and GOPDC is believed to have used its own capital (through Siat, the Belgian parent company) to finance its AD investment.

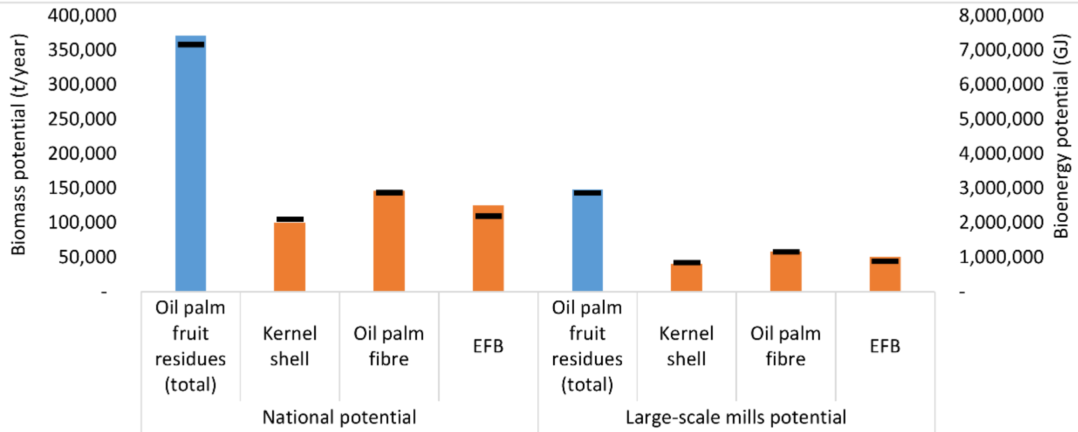
5 Potential for wider adoption

This section assesses the replicability potential of the Bioenergy Case in the oil palm sector, considering the five research themes of biomass resources, technology, economic benefits, commercial potential and the institutional and regulatory framework.

5.1 Biomass resource assessment

5.1.1 Biomass potential from oil palm residues

From its annual crop of ~2.6 Mt of oil palm FFB (FAO, 2020), Ghana generates around 371 kilo-tonnes (kt)/yr, dry basis (d.b.) of solid residues, with an energy potential of ~7.2 million GJ (see Figure 5-1 for breakdown and Appendix 3 for calculations), plus 1.95 Mt of POME, with a biogas potential of ~54.7 million Nm^3.



	Oil palm fruit residues (total)	Kernel shell	Oil palm fibre	EFB	Oil palm fruit residues (total)	Kernel shell	Oil palm fibre	EFB
	National potential				Large-scale mills potential			
Biomass potential (t dry basis)	370,865	100,008	145,846	125,011	148,346	40,003	58,338	50,004
Bioenergy potential (GJ)	7,161,022	2,100,178	2,873,160	2,187,685	2,864,409	840,071	1,149,264	875,074

Figure 5-1. Biomass and bioenergy potential from oil palm solid processing residues in Ghana

Only about 40% of the FFB are processed in large commercial mills, where the solid and liquid residues are aggregated and accessible. The remaining 60% are processed in traditional small-scale sites, which effectively prevents mobilisation of the residues and use for bioenergy applications. The commercial mills generate around 148 kt/yr of solid residues (d.b.) with an energy potential of ~2.9 million GJ. There are some competing uses for the solid residues, which are used as compost at larger estates, while shells can be used for road surfacing and construction (Ofosu-Budu & Sarpong, 2013).

As shown in Figure 5-2, the large mills also produce around 781 kt/yr of POME, with a biogas potential of 22 million Nm^3. Assuming methane content of 55% as measured at GOPDC, this would equal an energy content of about 0.4 million GJ.

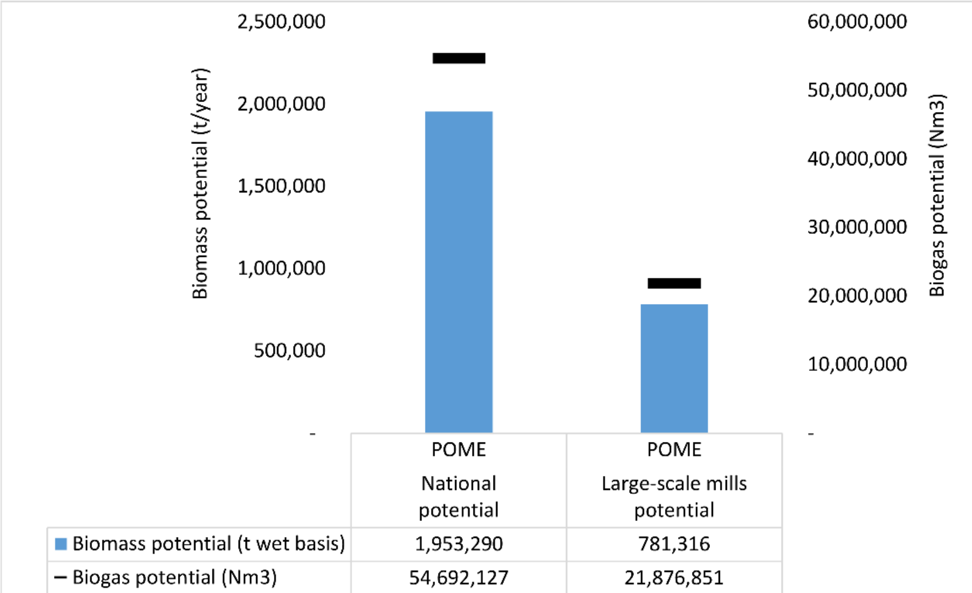


Figure 5-2 Biomass and biogas potential from POME in Ghana

5.1.2 Mass-energy balance

Table 5.1 shows the mass-energy balance (MEB) parameters for an AD plant in the oil palm sector. The input data are based on the specifications of the GOPDC facility.

Table 5.1: Mass-energy balance, POME-based AD

Parameter	Unit	High-pressure steam	Low-pressure steam
Model input parameters			
Energy installed	kW	700 kW_{th}	3.8 MW_{th}
Capacity factor	%	80%	
Annual operational hours	hrs	7,008	
Operational pressure	Bar	70	12
Operational temperature	°C	291	195
Moisture content as received	%	95%	
Volatile matter content	%	85%	
Efficiency	%	Heat: 90%	
Methane content of biogas	%	55%	
Model outputs			
Biomass flow	kg/s (wet basis)	2	10.8
	t/yr (wet basis)	50,233	272,691
Biogas production	Nm^3/s	0.04	0.21
	Nm^3/y	974,131	5,288,141
Biogas/biomass (wet basis)	Nm^3/ t	19.4	
MWh heat/t biomass (wet basis)	MWh_{th}/t	0.1	
Steam production	kg/s	0.5	1.9
	t/yr	12,042	48,665
Energy output			
Electricity	MW_e	n/a	
	MWh_e/yr	n/a	

Parameter	Unit	High-pressure steam	Low-pressure steam
Heat	MW_{th}	0.7	3.8
	MWh_{th}/yr	4,906	26,630
Loss	MW	0.08	0.42
	MWh/yr	545	2,956

The Mass-Energy Balance modelling considered heat generation only, using biogas produced from POME in a 700 kW_{th} high-pressure and a 3.8 MW_{th} low-pressure boiler. The MEB model cannot simulate two concurrent steam outputs as their temperatures, pressures and flow rates differ, which means the outputs will not be a direct representation of the reality at GOPDC, and will also explain why some of the energy output figures differ from those in the technical and economic analyses within this report. Instead the model provides an estimation of the amount of POME that will be needed to meet the give low or higher pressure requirements at a specific capacity factor.

In a low-pressure steam option, the MEB model calculated a steam flow of 1.93 kg/s, compared to 0.48 kg/s in a high-pressure option (pressure and temperature provided in Table 5.1). The high-pressure option can produce 0.24 t of steam per m^3 of POME, compared to 0.18 t of steam per m^3 of POME in the low-pressure option, meaning about one third of more steam production in the high-pressure system.

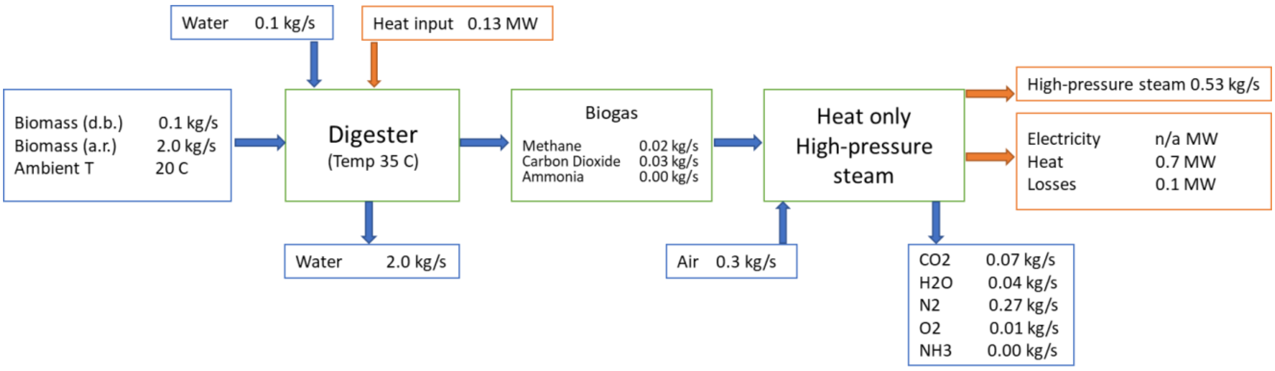


Figure 5-3: Mass-energy balance high-pressure steam, based on input specifications at GOPDC

Based on the MEB modelling, 50,233 t POME are required to generate 0.7 MW of heat in the high-pressure boiler. With an availability of 195,000 m^3 POME at the GOPDC facility, which equals about 170,820 t POME about 2.4 MW high-pressure steam could be generated (Ali & Tay, 2013). The low-pressure boiler would require 272,691 t POME when run at 90% capacity. This would be beyond the available POME at the facility. About 2.4 MW low-pressure steam could be produced from the 195,000 m^3 POME available. However, both boilers (high-pressure and low-pressure) do not run at this capacity in parallel and would depend on the actual demand for the different types of steam during the processing. Considering the oil palm production in Ghana and the potential for 1.95 Mt POME, this could provide a total of about 27 MW of high-pressure or low-pressure steam produced from POME-based biogas.

Based on the modelling assumptions and input data, a biogas yield of about 19.4 Nm^3 per tonne of POME is achieved for the GOPDC system. This is considerably less than the optimal yield of 28-35 Nm^3 of biogas per tonne of POME (Suksong et al., 2020). This is likely to be due to the low solids content of about 5%.

5.2 TECHNOLOGY

Given the unfamiliarity with commercial-scale biogas technology in West Africa and the relatively low-cost of combustion-based systems for CHP, the obvious first choice for a palm oil company looking to convert processing residues to energy is to install a combustion-based CHP system fuelled with solid processing residues. This is a mature technology with well-established equipment providers, increasingly from south and southeast Asia (rather than Europe and North America, as was the case before). Combustion-based CHP has already been adopted by Ghana's six leading oil palm processors. AD is a supplementary option likely to be confined to two processors with additional heat requirements, and a commitment to valorisation and environmentally sound disposal of POME. In other countries with more expensive and unreliable grid power, AD might also offer a source of electricity (as it does at Siat's Presco palm oil facility in Nigeria).

While the design and supply of modern AD technology has been dominated by companies in developed economies, largely servicing customers in their own regions, the landscape for technology supply to tropical agro-industries such as oil palm producers is inevitably somewhat different. The market for these specialised companies is mostly in SE Asia, South America and West Africa. European and North American AD companies targeting the palm oil industry have therefore adopted a different commercial model to those that provide equipment for livestock wastes or residues from temperate agriculture. These suppliers derive their core business from emerging economies, not from the industrialised North, and have reoriented their operations accordingly.

Biotec is a leading example, with a Belgian head office but subsidiaries in Colombia, Malaysia and Indonesia that take a lead on business development and project management. Another example is **Solmax Bioenergy** of Canada,[12] which has installed over 20 POME AD plants in SE Asia and also has active subsidiaries in Malaysia and Indonesia. Solmax manufactures HDPE membranes and, after acquiring **Geosynthetica Environmental** in 2017, dominates the supply of this material, of which 2-3 ha are required for a typical POME AD plant. At the larger end of the scale is the multinational **Veolia**, which has developed a multi-tank 'POMETHANE'® AD process that operates in the thermophilic range at 52°C.[13] Veolia has found synergy between its global wastewater treatment capabilities and the POME valorisation opportunity, though is not yet thought to have installed any AD plants in Africa.

Various technology suppliers have also supported non-POME AD installations in Ghana. **Nijhuis Industries** of the Netherlands,[14] for example, has been involved in at least one Dutch-funded AD project in Accra based on municipal waste.[15] But these are limited procurement arrangements for the supply of standardised components.

[12] www.solmaxbioenergy.com
[13] www.veoliawatertechnologies.com/sites/g/files/dvc2476/files/document/2019/03/brochure_pomethane_0912.pdf
[14] www.nijhuisindustries.com
[15] www.safisana.org/projects/safi-sana-factory-1-ashaiman/

The leading technology providers to the oil palm sector offer integrated partnerships, rather than one-off equipment sales. This is vital to build customer confidence in an immature market. Like most SSA countries, Ghana has limited local expertise for managing sophisticated AD plants, which require particular skills in operation and maintenance, and in monitoring and adjusting the biological process to ensure stable biogas generation. Biotec's POME specialisation and a commitment to extensive onsite training gave GOPDC sufficient confidence to invest. A Belgian connection via GOPDC's parent company may have been an additional determining factor.

Suitable technology for POME-based AD has been fine-tuned across Latin America and SE Asia over the 30+ years, since the first AD plant for POME was established. Biotec is the market leader in West Africa, with successful installations in both Ghana and Nigeria. Technology is therefore not considered a barrier to the replication of the GOPDC model. Wider adoption is more likely to be constrained by factors addressed elsewhere in this report, primarily lack of internal demand for heat beyond that which combustion-based systems can comfortably supply, access to relatively cheap and reliable grid power, and limited enforcement of controls on POME treatment and disposal.

5.3 Economic competitiveness

Adjustments were made to selected parameters in the LCC toolkit to determine their impact on LCOE, and the implications of these changing costs for the replication potential of the Bioenergy Case.

For the introduction of AD in the palm oil sector, the key parameter investigated in the sensitivity analysis was the thermal energy demand for the refinery operations.

Figure 5-4 shows the linear regression line of 125 simulated scenarios, for both the Bioenergy Case and the Base Case. The current heat demand at the refinery is 14,470 MWh_{th} per year, which is only just above the tipping point of economic viability of this investment in an AD plant. For an operation with similar input specifications, heat demand below that level would not justify such investment, while higher heat demand would result in lower LCOE values for the Bioenergy Case.

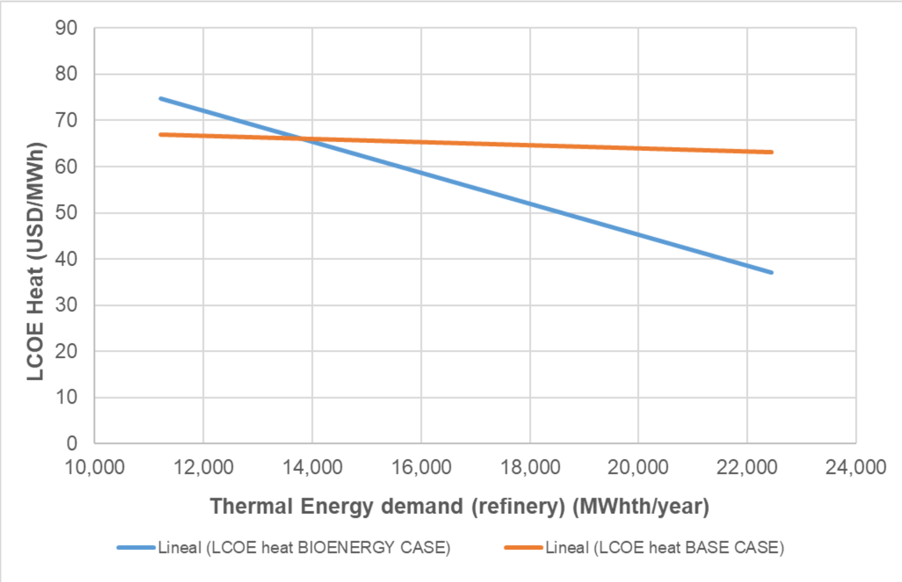


Figure 5-4. Sensitivity of $LCOE_{heat}$ to total refinery heat demand

Another parameter considered in the sensitivity analysis is the price of diesel, as the consumption of diesel is an important component in the LCOE breakdown in Figure 4-2. The analysis in Figure 5-5 shows that the Bioenergy Case is less sensitive to changes in diesel fuel price than the Base Case (as indicated by the shallower line gradient), since diesel consumption is lower than it is in the Base Case. The LCC model shows that a drop in the cost of diesel to about USD 0.71/l (from the current level of USD 0.95/l) would hinder the attractiveness of investing in AD from a purely financial perspective.

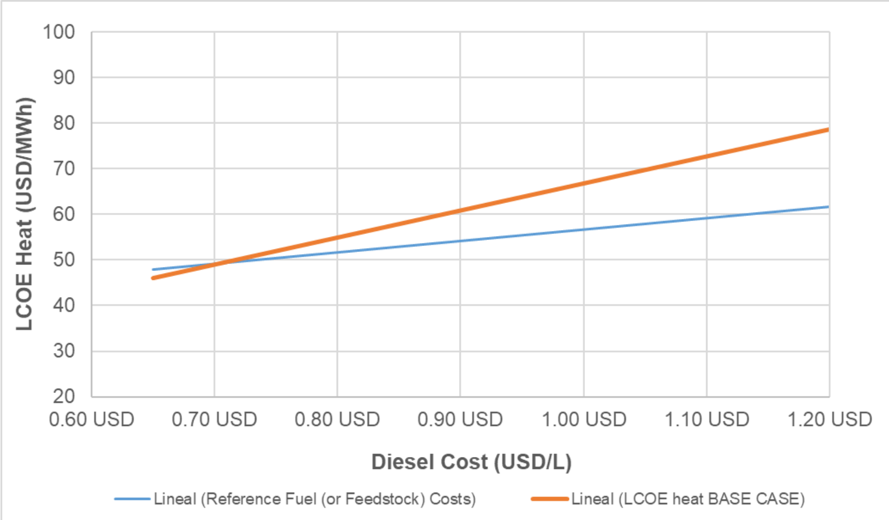


Figure 5-5. Sensitivity of $LCOE_{heat}$ to diesel cost for boiler co-firing

Finally, the effect on $LCOE_{heat}$ of POME treatment cost was investigated, for a range from USD 0 to 25/m^3, based on comparable reference examples (Ahmad et al., 2009). See Figure 5-6. The results show that if the avoided cost of POME treatment is considered in the economic model, then the investment in an AD plant is shown to yield much more significant savings in the cost of heat supply than the basic analysis that considers only diesel savings.

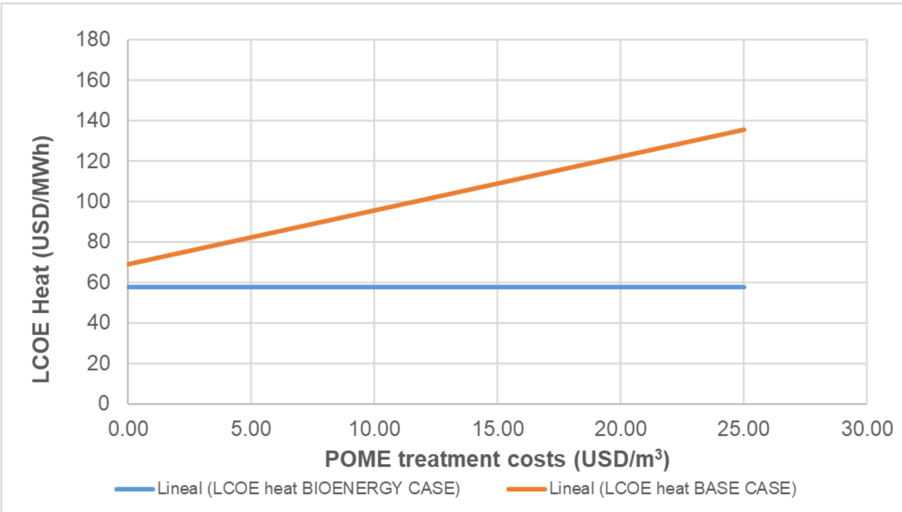


Figure 5-6. Sensitivity of $LCOE_{heat}$ to POME treatment cost

5.4 COMMERCIAL PROSPECTS FOR REPLICATION

5.4.1 Market potential

312,000 t of palm oil was produced in Ghana in 2018 (FAO, 2021). Given that 40% of this is processed at large mills, and assuming that 100% of their output was refined (which is not currently the case), then the estimated process heat demand for industrial-scale refining would be ~18 GWh_{th} per year.[16] Based on the biomass resource assessment in 5.1.1, the largest oil mills generate an estimated 781 kt/year of POME, sufficient to generate 22 million Nm^3 of biogas, which can produce about 110 GWh_{th} of bioenergy, assuming a conversion efficiency of 90%.[17] This indicates that there is sufficient POME from the country's large mills to meet the potential heat demand, assuming that they all wished to refine 100% of their output.

The actual commercial replication potential of POME-based AD technology is likely to be limited for commercial reasons, however, because only two of the major processors have on-site oil refineries and so have no supplementary heat demands that cannot be met by their combustion-based CHP systems alone.

5.4.2 Market barriers

The key barriers and enablers that determine the commercial replicability of AD at palm oil facilities are linked to heat demand for self-consumption, electricity demand (for both self-consumption and grid export), POME disposal requirements and the valorisation of digestate (Table 5.2).

[16] Assumes typical palm oil refinery heat demand of 129 kWh_{th} per tonne of refined palm oil (Sulaiman et al., 2012).
[17] Assumes biogas LHV of 19.7 MJ/Nm3 (with 55% CH4 @ 36 MJ/Nm3), giving 433,400 GJ, or 120 GWh,

Table 5.2. Summary of commercial barriers and enablers for POME-based AD

Demand source	Barrier to business model	Enabling conditions
Heat for self-consumption	**Combustion-based CHP already generates sufficient heat for most factory operations** Most oil mills can meet their heat requirements from combustion-based CHP using their own solid residues, plus additional purchased feedstock, by drawing low pressure exhaust steam from their electricity turbines. The only processors with additional demands are those with oil refineries, of which there are just two in Ghana.	**Presence of an oil refinery requiring additional heat** If the heat output from a CHP unit is insufficient to meet a mill's internal demands, perhaps due to insufficient availability of solid residues, then mills tend to buy in additional feedstock. A case for AD only seems to exist if a refinery is present, with a requirement for high pressure (e.g. 70 bar) steam. This is not automatically the case, however. There is a refinery at Juaben, Ghana's sixth largest mill, but they intend to upgrade their existing CHP plant with a larger (1.25 MW) turbine that will provide sufficient additional steam to meet their entire need for heat and power needs, without the need for AD. Opportunities are therefore limited, unless additional refineries are built in the country.
Electricity for self-consumption	**CHP systems and cheap grid power already provide sufficient electricity for self-consumption** Combustion-based CHP systems already provide a source of electricity for self-consumption at the six largest oil mills, and supplementary grid power is abundant, competitively priced and relatively reliable. An additional investment in AD to provide more power would be more costly than buying additional power from the grid.	**No viable enabling conditions exist, unless grid power becomes unexpectedly expensive or less reliable** With all large mills able to meet their electricity needs through a combination of combustion-based CHP and inexpensive grid electricity, there is no motivation to invest in AD for supplementary power for own use, unless the ECG tariff increases or the reliability of supply decreases. This may not be the case in other countries with higher power tariffs or less reliable grids.

Demand source	Barrier to business model	Enabling conditions
Electricity for grid export	**Oversupply of cheap power makes grid sales uneconomic** An excess of electricity on the national grid means there is no market for bioenergy electricity sales to the ECG. Additional regulations that permit Independent Power Producers to sell electricity directly to other consumers have been suspended, ruling out the option of making direct sales from an oil palm mill to another user.	**No viable enabling conditions unless tariffs are raised and grid feed-in is encouraged** Without the possibility of selling power to the grid at an attractive tariff, there is no reason for an AD plant to generate surplus power for sale to the power utility.
POME disposal requirements	**Alternative methods to treat POME are already in place** POME treatment using aerobic lagoons can reportedly meet the EPA's effluent disposal standards for COD and BOD, and there are no restrictions on methane emissions. Some plants (e.g. Juaben) use a specialist effluent management company to ensure that the effluent meets the required specifications (e.g. by surface skimming).	**Ensure stringent enforcement of POME treatment and disposal standards** It is important for environmental protection that POME is disposed of safely and responsibly, and that government standards for doing so are properly enforced. But biogas plants are only one of the technical options for managing POME, and may not be the most cost-effective solution if the primary objective is simply to render the effluent benign.
Digestate valorisation	**Current lack of opportunities to valorise digestate** The potential value of POME AD digestate as a soil improver was not part of the AD investment case at GOPDC.	**Conduct trials on using digestate as a fertiliser** GOPDC is trialling the use of the liquid digestate as fertilizer, and whilst early signs appear promising, accurate agronomic data has not yet been collected. If the benefits were recorded and quantified, the economic case for AD would be boosted as a result of lower costs of fertilizer purchase.

5.4.3 Ownership structure and financing approach

As explained, GOPDC used its own capital (through Siat, the Belgian parent company) to finance its AD project, and raising finance internationally for this project does not appear to have been a major barrier. Despite the vibrancy of Ghana's finance and banking sector, the limited track record of commercially proven AD projects in the region makes it probable that other large-scale palm oil processors would also have to provide their own capital for such projects, and will not be able to access loans locally.

Even if they could do so, interest rates close to 20% would be punitive. No evidence was found of external development financiers being engaged to provide funding for projects of this type in this region, or at this scale. Provided that a developer can secure finance internationally, and is not reliant on local institutions who are unfamiliar with lending in the AD sector, finance *per se* does not appear to be a barrier to the adoption of AD in Ghana's palm oil industry. Rather it is the lack of a sufficiently strong business case.

5.4.4 Conclusions

GOPDC is the largest palm oil mill in Ghana, and has a refinery that requires considerably more heat than its pre-existing CHP unit can supply. This was the main driving force behind the AD investment. As an internationally owned company, GOPDC also has a strong interest in environmental accountability to its customers, a need that can be met by AD's ability to dispose of POME safely and responsibly. Being part of a larger multinational firm enabled GOPDC to raise finance internally.

Although POME is plentiful in Ghana's industrial palm oil industry, the wider deployment of AD is commercially unattractive. Large producers already have combustion-based CHP plants that meet their requirements for process heat and contribute to their power needs, with the balance of electricity purchased cheaply from the grid. Electricity export is not possible under current conditions. Only those processors with oil refineries have additional demand for heat that can be met by AD, and they are just two in Ghana, and there are alternative POME treatment solutions. Norpalm commissioned an AD feasibility study by Biotec in 2015, but it was rejected by their Board - likely for these reasons.

Other motivations such as stronger environmental enforcement and digestate valorisation are unlikely to make the commercial case significantly stronger, although should digestate be proven to be an effective fertiliser for palm plantations, this may improve the business case in future.

5.5 Gender and inclusion

In Ghana, the engagement of women in commercial agriculture has increased, although they still face disadvantages in gaining access to support or reaping the economic benefits of increased productivity (Ayentimi et al., 2020). Many of the gendered differences within oil palm production are linked to land ownership issues, access to productive assets and women's opportunities to be involved in economically fruitful activities, for which numerous cultural barriers are reported. From the limited examples available, it was found that there are some examples of attempts at ensuring gender inclusion is, at least, not at the Gender and Inclusion 'Blind' stage, and could be seen to shifting into the GESI 'Sensitive' stage[18] Any further investments to replicate AD (as the Bioenergy Case in this demand sector) should take these considerations into account.

Care should be taken to ensure that commercial palm oil operations are equipped with gender-sensitive policies and support mechanisms, for both male and female workers at the company level. This is relevant for plantation and out-grower operations, as

[18] GESI Unequal: perpetuates inequalities; GESI Blind: ignores inequalities; GESI Sensitive: acknowledges but does not address inequalities; GESI Specific: considers and addresses inequalities; GESI transformative: aims to transform unequal and harmful inequalities. (WHO, 2011)

well as bioenergy-based factory operations. There is already some evidence of this approach in Ghana's industrial-scale oil palm operations, ensuring that support is provided for female inclusion - such as flexible working conditions for pregnant workers, to prevent women being unfairly disadvantaged in carrying out their duties. Consideration should be given to creating a committee, with equal male and female representation, tasked to deal with GESI issues in more depth. Such a committee could provide an unbiased platform for workers to express their concerns and feed into any policies or procedures being developed. It could also provide a safe space for gender-based violence or harassment to be reported, which should align with company-level zero-tolerance policies. These committees would also work with community-level farm workers, to ensure capacity building is provided both for female and male employees and out-growers. Where female inclusion opportunities are created, care should be taken to ensure that women feel able to capitalise on them, which requires an understanding of how increased female empowerment could impose negative impacts at the household level.[19] Any expansion or investment should be aware of, and engage with, civic international NGO groups currently working in G&I issues. The RSPO, for example, has produced a guide on gender inclusion and compliance, which should be consulted (Senders et al., 2020). In addition, there should be awareness and integration of learning from existing legislation, legal and policy reforms. For example, best practice based on the Ghanaian National Gender and Children's policy, which works to strengthen and streamline gender concerns into development agendas. In addition the Government of Ghana has developed a Master Plan Study for the Oil Palm Industry in order to prioritise equitable access to productive resources for all farmers (Appiah, 2018).

5.6 Institutional, market and regulatory framework

As previously noted, significant investments have been made in Ghana in fossil fuel generating capacity over the past decade, to meet major electricity shortfalls that came about in the 2000s. As noted in Section 3.3.2, the Energy Commission suspended licensing any renewable electricity plants in 2018 (Research & Markets, 2019).[20] This has significantly stifled investment in grid-based renewable electricity, a situation that will last for a number of years. This effectively prevents bioenergy development for electricity generation, except for own-consumption, given the very large surplus of primarily fossil fuel electricity generation. This surplus, therefore, significantly constrains investment in power generation from AD or combustion-based CHP using oil palm residues .

It is hoped that the new National Energy Plan, currently under legislative review, will break this bottleneck to encourage bioelectricity generation into the grid in the near future, particularly in rural areas with weak electricity infrastructure, which often results in power outages that affect industries (e.g. palm oil) and commercial and household consumers. The hope is that the NEP will take into account the benefits of embedded generation from renewable energy (e.g. from the palm oil mills, among other renewable sources) to help strengthen the grid. While this looks unlikely now or in the short term, those promoting renewable electricity to meet Ghana's

[19] Such as increased gender-based violence at the household level.

[20] This excluded Bui Power Authority (BPA), an autonomous power authority focused on the Black Volta BUI hydropower storage facility established by Act of Parliament (Republic of Ghana, 2007) to regulate both water flow on the Volta River as well as peaking load on the national grid.

environmental targets (including reducing GHG emissions from fossil fuel electricity generation) will be making this case for embedded generation to strengthen weak rural grids.

In the meantime, the AD opportunity at palm oil processors depends primarily on internal demand for heat, above that which combustion-based CHP systems can satisfy, which is limited to the small number of mills that have refineries on site.

5.7 Replication potential in other target countries

5.7.1 Introduction

This section explores the potential for wider adoption of the Bioenergy Case in the other BSEAA2 target countries. The intention is to summarise the prospects for replication of the model, based on the commercial environment in each of those countries and their respective palm oil sectors, where applicable, but not to quantify either total energy demand in the sector, or the potential scale of the replication opportunity.

5.7.2 Country profiles

Of the ten SSA countries in the BSEAA study, Nigeria is the fourth largest palm kernel oil producer in the world, and Ghana is the fifth. Smaller producers such as Kenya, Mozambique, Tanzania and Uganda could also benefit from successful practices developed in Ghana.

Kenya: Oil palm was introduced to Kenya in 1992, with FAO support, as an alternative to sugarcane. A cold-tolerant variety was piloted by the Mumias Sugar Company in areas previously thought unsuitable for commercial cultivation (FAO, 2003; FarmLINK Kenya, 2018). Studies by the Kenya Agricultural and Livestock Research Organisation (KALRO) showed that oil palm was viable, particularly in the west of the country, offering potential as an alternative cash crop for smallholders (FarmLINK Kenya, 2018). Government support has been variable, however, and the crop is yet to take off on a large scale. Kenya is a major consumer of palm oil in SSA and relies on imports of close to 1 Mt p.a. of CPO, due to negligible local production. Bidco Africa, a large agro-processing industry, is the major player in the country's palm oil industry, both for imports (which make up over 95% of BIDCO's palm oil production) and for the small amount produced by dispersed Kenyan smallholders.

Mozambique: Mozambique does not have any sizeable palm oil production, though it is a major consumer and imports nearly 350,000 t of palm oil p.a.. Singapore-based Olam International has a local factory that is understood to process imported CPO (crude palm oil) into refined palm oil (Selina Wamucii, 2020). There were a number of plans for investments in industrial oil palm plantations in Mozambique in the early 2010s. None of these projects have materialized. Mozambique remains a large net importer of palm oil, while its farmers produce very small quantities of palm oil on an artisanal scale for local consumption.

Nigeria: Nigeria produces just over 1 Mt p.a. of palm oil making it the 5th largest producer of palm oil in the world (USDA IPAD, 2021). Ghana, by comparison, ranks 13th with less than a third of Nigeria's production. Nigeria exports a significant proportion. It is also the largest consumer of palm oil in Africa, with domestic demand of 1.34 Mt p.a., making it a net importer.

The oil palm belt covers 24 states, of which nine in the Niger Delta account for 57% of total production. Despite being a leading producer and consumer, Nigeria's palm oil industry is highly fragmented and dominated by smallholders who mainly harvest semi-wild plants. These farmers produce roughly 80% of total output, on between 1.6 and 3 million ha of land. Their dominance results in low overall productivity, as a result of outdated and wasteful manual harvesting and processing techniques. Oil palm estates cover between 169,000 and 360,000 ha, with at least 72,000 ha under large estates and 97,000 ha smallholder plantations (low-end estimates). While large plantations account for less than 20% of total oil production, the two largest producers – Okomu and Presco[21] - have a significant combined capacity compared to smallholder farmers (Siat Group, 2018). Siat has two plants in Nigeria, of which one, Presco, has a large AD facility. Unlike the plant at GOPDC, this is used for generating electricity.

Tanzania: Palm oil is the most widely consumed edible oil in Tanzania, with consumption of just over 0.55 Mt p.a. of CPO, of which 98% is imported, mainly from Southeast Asia, and refined in Dar es Salaam by a handful of companies. 80% of Tanzania's small palm oil output comes from Kigoma Region in the far west, with over 30,000 smallholder farmers practising very small-scale palm oil-based mixed cropping system, mostly for own consumption, but where revenues from locally, artisanal-produced palm oil constitute at least 30-50% of their farm revenues. Farmers either process their own FFBs using traditional human-powered machines or sell them to other farmers who process collectively (Camco Clean Energy, 2014). Production and processing methods are traditional and characterized by very low productivity. In order to stimulate the local palm oil industry, the tariff on imported CPO was increased in 2018 from 10% to 25%, and on semi-refined and refined palm products from 25% to 35%. While this is likely to increase prices in the short term, as there is no ready domestic production to fill the supply gap, the Government plans to invest USD 4.3 m to boost domestic cultivation of oil palm over the medium to long term (Temu et al., 2013).

Uganda: Uganda has only been growing palm oil commercially since the early 2000s, with the establishment of its first plantations on Bugala Island in Lake Victoria in 2003. This was a Public-Private Producer Partnership through the Ministry of Agriculture, Animal Industry and Fisheries, with support from the International Fund for Agriculture Development (Friends of the Earth International, n.d.). Close to 11,000 ha of oil palm have now been planted on the island, of which 6,500 ha are managed by the private sector partner, Oil Palm Uganda Limited (OPUL) (BIDCO, 2021), and the rest by smallholder farmers. OPUL is a joint venture between Wilmar Group (Malaysia), Josovina Commodities (Singapore) and Bidco Oil Refineries (Kenya, registered in Uganda as Bidco Uganda Ltd.). OPUL has established two palm oil mills on the island and a processing plant in Jinja. The Government of Uganda established the Kalangala Oil Palm Growers Trust (Meyerhoff, 2018) to provide extension support to farmers and act as intermediary between smallholders and OPUL. This is a controversial project for environmental reasons, and OPUL is accused of 'land grabbing'.

[21] Presco is owned by Siat Group, the same company that owns GOPDC in Ghana. Presco also commissioned Biotec International to design and install a POME-based AD system, the largest in Nigeria, which generates power as well as heat.(Siat Group, 14 August 20201)

5.7.3 Summary of replication potential in other target countries

With the exception of Nigeria, which produces four times as much palm oil as Ghana, the other BSEAA2 target SSA countries do not even rank in the top 30 producers in the world, as they have either only recently introduced oil palm or have not expanded production since introduction, and extract oil on a small-scale using artisanal techniques. It is therefore difficult to use Ghana as a comparator, as oil palm production and palm oil consumption have been important agriculture and dietary elements of Ghanaian culture for many centuries, and 40% of output is now processed at large industrial-sale mills.

Nigeria is the exception amongst the ten target countries. Oil palm is a major crop for millions of Nigerian farmers and its cultivation and dietary use closely mirrors that of Ghana. Unlike Ghana, Nigeria has significant shortages of electricity and a very poor national power infrastructure.

Policy incentives have been put in place in Nigeria to promote large-scale palm oil production and to rehabilitate formerly successful oil palm estates. Based on the example of Siat at Presco Nigeria, the potential for obtaining significant value-added from AD for electricity production beyond self-consumption is enormous (Obuka et al., 2018). Under Nigeria's current electricity sector regime, guided by the Nigerian Electricity Regulatory Commission, significant opportunities exist for licensing renewable electricity IPPs in Nigeria, with relatively high USD-tied FiTs for biomass-based renewable electricity (Federal Republic of Nigeria, 2015).

This is not the case in Kenya, Mozambique, Tanzania and Uganda, where almost all palm oil is processed artisanally, with no medium-to-large-scale palm oil processers. Most of the palm oil is produced is for own consumption or local sale, with little potential for growth. There is, therefore, little possibility that the palm oil sector will grow large enough in these four countries to have large processing facilities such as GOPDC in Ghana and Presco in Nigeria, with AD units producing heat and/or electricity.

The edible oil companies in these four countries (e.g. BIDCO in Uganda and Kenya, Olam in Mozambique) buy some palm oil from small-scale farmers. Although they process a variety of edible oils, for which energy is required, their operations are located in urban areas away from potential sources of palm oil residues, and they are connected to national grids, so lack both the feedstock and demand for AD based on palm oil resides.

6 SUMMARY AND CONCLUSIONS FOR REPLICATION

Large estates with on-site mills account for about 40% of Ghana's palm oil output, and have sufficient throughput, financial capacity, energy demand and human resources to support investments in modern bioenergy technology. The six largest processors have installed combustion-based CHP plants that use solid oil palm residues for generating electricity and process heat for meeting their on-site energy requirements. One processor (GOPDC) also uses POME as feedstock for an AD system to generate biogas, which supplies heat to its on-site oil refining operation.

Based on the analysis of GOPDC's experiences, a multi-criteria analysis (MCA) was carried out to summarise the degree to which each of the study's five thematic strands are conducive or detrimental to the successful adoption of POME-based AD in the palm oil processing sector in Ghana. The results are presented in Figure 6-1, with a low score indicating an impeding factor and a high score indicating an enabling factor (see Appendix 5 for scoring details).

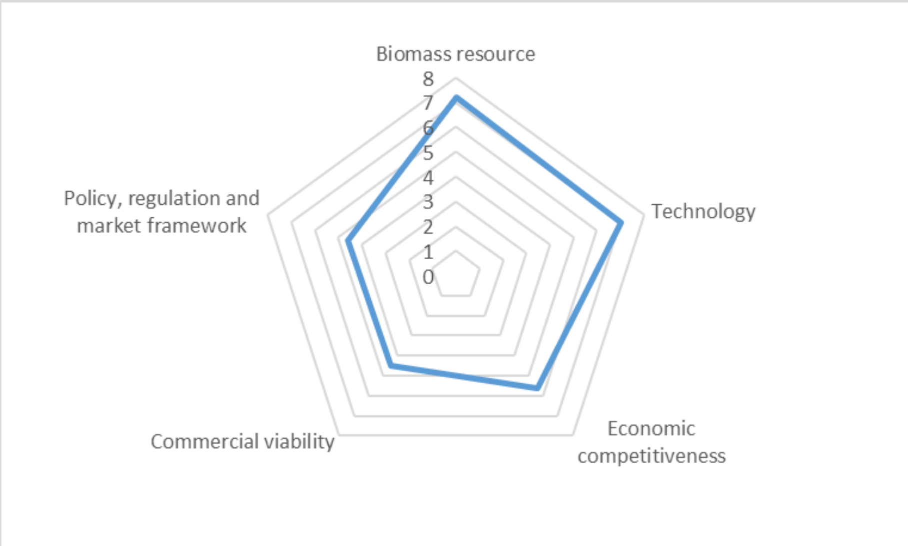


Figure 6-1 Impact of key factors on wider adoption of bioenergy case

Biomass resource assessments indicate that there is sufficient POME available at Ghana's six largest palm oil processors to meet the potential heat demand if they wished to refine all their crude palm oil (although only two of them currently have refineries). Feedstock supply is therefore not a barrier to wider replication of GOPDC's AD investment for heat production, although seasonality of POME supply is a constraint to full year-round productivity of POME-based AD.

Based on the experiences of GOPDC and specialist developers of AD solutions for the palm oil industry, technology selection, sourcing and operation is not a constraint to wider adoption of AD in this sector. Technology for POME-based AD has been fine-tuned across tropical regions over the past 30 years. The leading providers offer integrated partnerships, custom-built designs and extended on-site training, which is vital to engender customer confidence in immature markets such as West Africa.

The economic viability assessment indicates cost savings from AD by substituting for diesel to generate heat. The need for supplementary process heat was probably the main driver for GOPDC's investment in AD. Demand for electricity was not a motivating factor, given sufficient availability of power from the company's combustion-based CHP plant and the national grid.

From a commercial perspective, the wider adoption of AD in Ghana's palm oil industry is hampered by the fact that all the large processors have combustion-based CHP plants that already meet their requirements for process heat and contribute to their power needs, with the balance of electricity purchased cheaply from the grid. Only one (Juaben Oil Mills), in addition to GOPDC, has a refinery with an additional demand for heat. However, Juaben's owners have decided to expand their combustion-based CHP capacity to meet this demand, rather than set up an AD plant. Other motivations for AD, such as more rigorous enforcement of POME treatment and disposal regulations, are unlikely to make the commercial case significantly stronger, given that there are less costly alternatives for effective POME management. While the efficacy of AD digestate as a fertiliser for oil palm plantations is not yet fully determined, this may improve the business case for AD in the future.

The policy, regulatory and market context for electricity in Ghana is another key barrier to wider adoption of AD by palm oil processors. Significant investments were made in fossil fuel generating capacity to meet major electricity shortfalls during the 2000s, to the extent that Ghana now has an oversupply on the grid. This has led to virtually no new renewable electricity capacity on the grid being licensed by Ghana's Energy Commission since 2018. This has stifled investment in grid-based renewable electricity and effectively prevents bioenergy development for electricity generation, except for own-consumption, and significantly constrains investment in power generation from oil palm processing residues. It is hoped that the new National Energy Plan, currently under legislative review, will break this bottleneck to encourage biomass-based electricity generation into the grid in the near future, particularly in areas with weak electricity infrastructure.

The other target SSA countries have either only recently introduced oil palm or have been pursuing its development at very small-scale, using mostly artisanal techniques, resulting in a nascent or non-existent AD opportunity. Only in Nigeria, the world's fifth largest palm oil producer, where there are significant shortages of electricity and a poor national power infrastructure, do significant opportunities exist for licensing renewable electricity IPPs, with relatively high USD-tied FiTs for biomass-based renewable electricity using palm oil residues. This may offer potential for further development of POME-based AD in West Africa, similar to that already developed by Presco in Nigeria (as sister company to GOPDC), which is generating electricity for own use and export to the grid from POME-based AD.

In sum, although POME is a plentiful resource in Ghana's industrial palm oil industry, the potential for wider deployment of AD is limited, given that all the large processors already have combustion-based CHP systems for meeting their on-site energy demands, access to cheap and abundant grid electricity and an inability to export surplus power, at least for the time being. While there may be other commercial drivers for the adoption of AD, such as stronger environmental enforcement and digestate valorisation, replication potential is likely to be limited to those mills with an additional demand for process heat (e.g. from a refinery), which a CHP system alone cannot satisfy. Even here, it may prove more economically expedient to expand existing CHP systems if sufficient solid oil palm residues are available.

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Appendix 2: People consulted

Organisation	Name	Position	Mode of contact
Benso Oil Palm Plantation	Edward Amankrah	Maintenance Engineer	Call
Biotec International	Philippe Conil	Managing Director	Call
Cleaner Production Centre (Ghana EPA)	Daniel Digber	Senior Programme Officer	Call
Energy Commission	Julius Nkansah-Nyarko	Bioenergy Policy Expert	Call
GOPDC	Evans Tenkorang	Utilities Head	In-person
	Jean Pierre Mvate	Chief Engineer	In-person
	Eugene Sarpong	HR Manager	In-person
	Bright Adomako	Administrative Officer	In-person
Juaben Oil Mills	Isaac Kyemase	Technical Manager	In-person
	William Kojo Mensah	Utility Head	In-person
	Isaac Ansu	HR Manager	In-person
	Ms. Ruth Adjei Boakye	Sustainability Officer	In-person
Norpalm Ghana	Emmanuel Nagel	Technical Manager	Call
SEforAll Secretariat, Ghana Energy Commission	Paula Edze	Coordinator	Call

Appendix 3: Assumptions in biomass resource assessment

The country-specific residual biomass potential was calculated based on amount of crop or primary product generated, the residue-to-product ratio, the recoverable fraction and the fraction of biomass available, considering other uses:

$$BMP=Cp*RPR*RF$$

Where: BMP = available residual biomass in tonnes per year
Cp = crop production in tonnes per year
RPR = residue-to-product ratio in tonnes of residues per tonnes of product
RF = recoverable fraction per tonnes of product after considering other uses per tonne of product

The theoretical bioenergy potential of this biomass resource was calculated considering the available residual biomass and its energy content.

$$BEP= BMP*(1-MC)*HHV$$

Where: BEP = bioenergy potential in GJ
BMP = available residual biomass in tonnes per year
MC = moisture content
HHV = higher heating value in GJ per tonne

Based on these calculations, resource availability and energy potential are summarised in the tables below.

Biomass resource assessment

Crop	Feedstock	Area of crop (ha/yr)	Annual production of FFB (t) [1]	Total biomass (t)	Recoverable fraction	Biomass potential (t wet basis)***	Moisture content as received (%) [2]	Biomass potential (t d.b.)	HHV (MJ/kg)	National bioenergy potential (GJ)***
Palm oil fruit	PKS	370,297	2,604,387	156,263	0.8	125,010	20	100,008	21	2,100,177
	Oil palm fibre			260,438	0.8	208,350	30	145,845	20	2,873,159
	EFB			390,658	0.8	312,526	60	125,010	18	2,187,685
	Totals (solid residues)	***370,297***	***2,604,387***	***807,359***	***0.8***	***645,887***	***43***	***370,864***	***19***	***7,161,022***
	POME	370,297	2,604,387	1,953,290	1.0	1,953,290	95 [2,3]	n/a	28[*,4]	54,692,127**

*Biogas yield (Nm^3/t fresh matter) **Biogas potential (Nm^3) *** figures indicate total national potential;

Biomass resource assessment (continued)

Feedstock	Production scale	Current use	Existing supply chain	Mobilisation
PKS	Small scale (dominant) and large scale	Residues returned to plantations as fertiliser, especially in small scale or collected by farmers from processing site; often disposed to land; increasingly used for bioenergy (onsite for oil palm processing)	yes	Can be mobilised as part of the palm oil processing supply chain, but requires additional handling, potentially storage of feedstocks.
Oil palm fibre				
EFB				
POME		Treated sludge returned to plantations as fertiliser where feasible; often disposed; increasingly used for bioenergy onsite for oil palm processing	Yes	

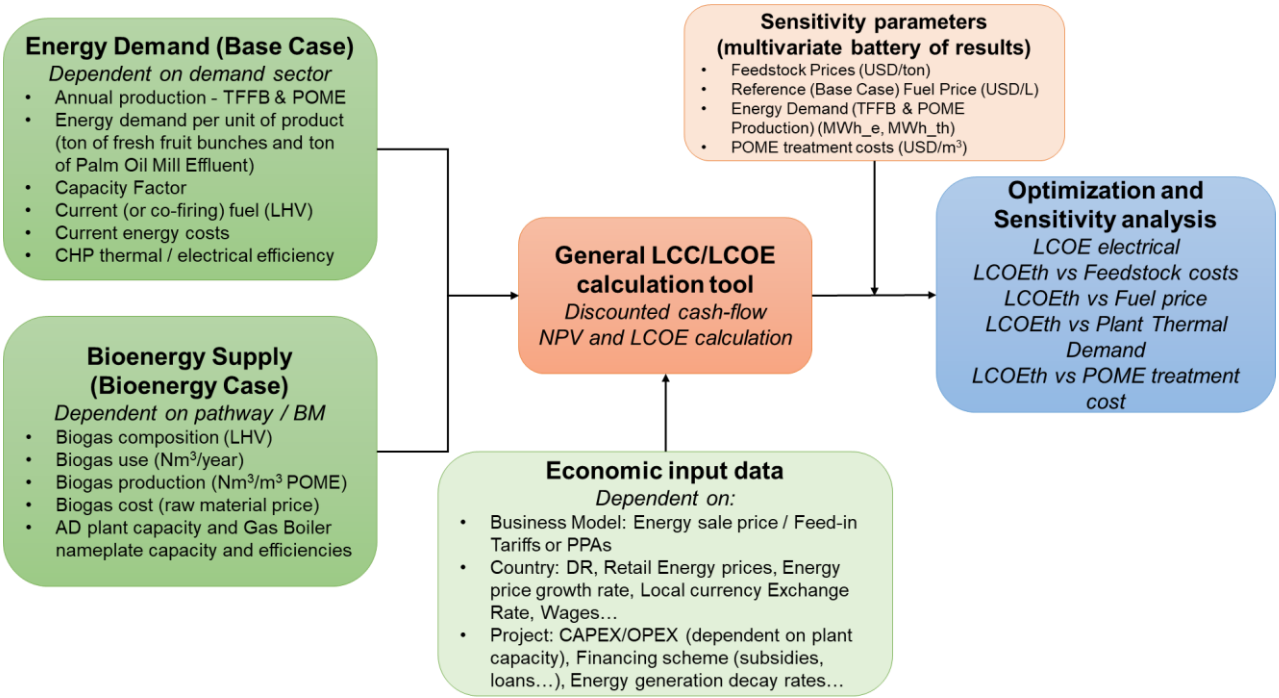
Residue-to-product ratios (RPR)

Residue type	RPR	Note
PKS	0.06	6% of FFB[2]
Fibre residues	0.10	10% of FFB[2]
EFB residues	0.15	15% of FFB[2]
POME	0.75	75% of FFB[5]

Sources: [1] (FAO, 2020); [2] (Elbersen, 2013); [3] (Yusoff, 2006); [4] (Suksong et al., 2020); [5] (Kamyab et al., 2018)

Appendix 4: Life-Cycle Cost toolkit functions

A flow diagram of AIGUASOL's Life-Cycle Cost (LCC) modelling toolkit functions is provided below:



The main economic indicator considered is the Levelized Cost of Energy (LCOE), in USD/MWh:

$$\mathrm{LCOE} = \frac{\sum_{t=1}^{n} \frac{C_t}{(1+DR)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+DR)^t}(1+IR)^t}$$

Where: C_t = costs incurred in year t
DR = discount rate
E_t = energy consumed in year t
IR = annual inflation rate

Appendix 5: Multi-Criteria Analysis input data

Criteria	Score	Scoring criteria (Min=1)	Scoring criteria (Max=10)
Biomass			
Availability	8	low	high
Seasonality	7	short	long
Aggregation	7	scattered	centralised
Proximity	7	far	close
Technical feasibility	7	low	high
Average	**7**		
Technology			
Technology track record in same sector	8	low	high
Availability of a turnkey technology solution	8	limited	well established
Ease of operation and maintenance with in-house capacity	5	limited	well established
Supplier reputation, engagement and partnership	7	not engaged	engaged
Access to technical support & spares	7	low	high
Average	**7**		
Business model			
Energy self-consumption drivers	5	limited	significant
Grid and 3rd party export drivers	2	limited	significant
Waste disposal drivers (based on cost for disposal)	8	limited	significant
Market potential (replicate business model)	3	low	high
Average	**5**		
Policy, regulation and market			
Bioenergy policy	5	unsupportive	supportive
Bioenergy policy implementation	1	not implemented	implemented
Agriculture/Forestry policy	7	unsupportive	supportive
Agri/Foresty policy implementation	7	not implemented	implemented
Demand sector specific policy	5	unsupportive	supportive
Environmental policy	6	unsupportive	supportive
Environmental policy implementation	3	not implemented	implemented
Technology-specific fixed price (e.g. FIT)	1	unattractive	attractive
Demand sector specific governance practice	5	weak	strong
Biomass/processing specific governance practice	6	weak	strong
Average	**5**		
Cost			
LCOE electricity total	6	cost increase	cost reduction
LCOE electricity CAPEX	8	cost increase	cost reduction
LCOE electricity OPEX non-fuel	6	cost increase	cost reduction
LCOE electricity OPEX fuel or electricity	4	cost increase	cost reduction
LCOE heat total	7	cost increase	cost reduction
LCOE heat CAPEX	1	cost increase	cost reduction
LCOE heat OPEX non-fuel	4	cost increase	cost reduction
LCOE heat OPEX fuel or electricity	9	cost increase	cost reduction
Average	**6**		

Appendix 6: Photos of GOPDC and AD System

GOPDC aerial view
(www.gopdc-ltd.com)

FFB at receiving area
(Francis Kemausuor, team member)

CHP boiler furnace
(Francis Kemausuor)

POME cooling towers
(Evans Tenkorang, GOPDC)

POME in holding tank
(Francis Kemausuor)

Digester inlet
(Francis Kemausuor)

AD plant overview
(Bulnes, 2017)

Agitator (recirculation pump)
(Francis Kemausuor)

1st stage digestate pond
(Francis Kemausuor)

Refined oil tank farm
(Evans Tenkorang, GOPDC)