Technical-economic Studies of Bio-Waste Valorisation for Local Multi-Energy System

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I declare that this document is an original work of my own authorship and that it fulfils all the requirements of the Code of Conduct and Good Practices of the *Universidade de Lisboa*.

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Abstract

Globally, substantial volumes of bio-waste are generated every day, causing severe environmental concerns, occupying soil, and demanding financial support for its management. An ingenious way of handling this bio-waste challenge is the expansion of modern and original methods focused on the alteration of these raw materials into value-added fuels. This work was conducted in the European Institute for Energy Research - a facility dedicated to energy subjects as well as the environment, and was motivated in order to research economic opportunities for investment in markets where energy costs and waste disposal costs are relatively high and where valorisation of bio-waste could be introduced. The work presents a choice of biogas digester for rural areas of French Guiana based on the MCA and the unit size based on the number of family members depending on the used feedstock. In addition, a business model of the pre-feasibility study for electricity production through rice husk gasification, was performed. Two models based on length of the rice mill operating hours were investigated and analysed.

Keywords

Bio-waste, biogas, valorisation, energy, power generation

Resumo

Globalmente, volumes substanciais de bio-resíduos são gerados todos os dias, causando graves preocupações ambientais, ocupando solo e exigindo suporte financeiro para seu tratamento. Uma maneira engenhosa de lidar com este desafio de bio-resíduos é a expansão de métodos modernos e originais focados na transformação dessas matérias-primas em combustíveis com elevado valor acrescentado. Os bio-resíduos e as possibilidades da sua valorização variam consoante a região de origem. Portanto, esta pesquisa combinou a avaliação técnica e económica de vários sistemas de transformação de resíduos em energia para a valorização de bio-resíduos e estudos de pré-viabilidade daqueles sistemas que para diferentes dimensões das unidades, tecnologias variadas, ambientes económicos distintos e diversos atores envolvidos. Este trabalho foi realizado no Instituto Europeu para Pesquisa Energética - uma instalação dedicada a assuntos de energia, bem como meio ambiente, e estava motivada no sentido de pesquisar oportunidades económicas de investimento em mercados onde os custos de energia e os custos de eliminação de resíduos são relativamente elevados e onde a valorização dos bio-resíduos pode ser introduzida. O trabalho apresenta uma escolha de digestor de biogás para áreas rurais da Guiana Francesa com base no MCA e o tamanho da unidade com base no número de membros da família dependendo da matéria-prima utilizada. Além disso, foi realizado um modelo de negócio do estudo de pré-viabilidade para produção de energia elétrica por meio da gaseificação da casca de arroz. Dois modelos baseados na duração das horas de operação da usina de arroz foram investigados e analisados.

Palavras-chave

Resíduos biológicos, biogás, valorização, energia, geração de energia

Table of Contents

List of Figures

List of Tables

List of Acronyms

AD	Anaerobic Digestion
AEM	Africa East Mediterranean
CAPEX	Capital Cost
CE	Circular Economy
EAP	East Asia and Pacific
ECA	Europe and Central Asia
EFB	Empty Fruit Bunch
EIFER	European Institute for Energy Research
FRP	Fiber-Reinforced Plastic
FW	Food Waste
GHG	Greenhouse Gas
HRT	Hydraulic Retention Time
IRR	Internal Rate of Return
LCA	Life Cycle Assessment
LCOE	Levelized Cost of Energy
LDN	Local Distribution Network
LPG	Liquefied Petroleum Gas
MSW	Municipal Solid Waste
NAM	North America
NGO	Non-Governmental Organisation
NPV	Net Present Value
OCD	Onsite-Constructed Digester
OPEX	Operating Cost
PBD	Prefabricated Biogas Digester
PH	Plastic Hard
PLN	PT Perusahaan Listrik Negara
PM	Particulate Matter
POME	Palm Oil Mil Effluent
PS	Plastic Soft
PV	Photovoltaics
SSA	Sub-Saharan Africa
WBT	Water Boiling Test
WM	Waste Management
WtE	Waste-to-Energy

List of Symbols

°C	Celsius degree
CO_2	Carbon dioxide
GWh	Gigawatt hour
kg	Kilogram
m^3	Cubic meter
MW	Megawatt
MWh	Megawatt hour
US$	American dollar

Chapter 1

Introduction

1.1 Overview

Energy systems of today are facing multiple challenges and developments, equally in the field of research, improvement, creation of policies, and local authorities' support. Meeting regularly restricting environmental targets is one of the main objectives for securing a defined path of modern energy services [1, 2].

The worldwide expansion of economic development and the enlarging population does not remain indifferent to the impacts on the environment. The first global climate deal - Paris Agreement, adopted in 2015, supports all nations in undertaking ambitious joint efforts to combat climate change by holding global average temperature increase below 2°C in relation to pre-industrial levels, with a particular focus on helping developing countries [3].

As energy resources are one of the main propellers for industry, processes involved in energy generation from conventional fuels contribute to emissions, many of which have an adverse impact on the ecosystem. Environmental concerns have led to the development and promotion of renewable sources of energy. The use of alternative fuels, mainly derived from organic waste materials, has a significant potential to mitigate global warming consequences, as they contribute to restoring carbon balance and are considered as carbon-neutral fuels. Introducing bio-waste as a renewable source of energy brings a possibility for attaining desired goals and successful transformation [4].

Environment compatibility is one of the essential characteristics of secondary fuels; therefore, it is expected that they will play a significant role in the formation of the future energy mix. Multiple sources of bio-waste materials, ranging from agricultural, municipal solid waste (MSW), industrial, and domestic, are a solid base for a broad spectrum of derived fuels used in scalable settings through waste-to-energy routes (WtE). The diversity of biofuels origin is as wide as possibilities and the scale of their applications [5].

1.2 Background

Solid waste and the factor of its rising generation is one of the significant problems’ societies have to face. This challenge can be addressed as a result of the linear economy being used as a putative pattern for many centuries, where the take-make-dispose approach has been applied. On the contrary, the closed-loop Circular Economy (CE) approach has gained much attention in the recent decade. The leading difference CE presents to the prior, adversarial concept, is using materials value and potential indefinitely, recycled of their properties, or returned to the natural environment without damage to the ecosystem (Fig. 1.1) [6].

Re-evaluating the structure of our economic system and enforcing CE can contribute to alleviating the problem of Waste Management (WM) both in the case of urban and rural areas. It also provides an answer to the limited availability of resources [7]. In the light of the gradual depletion of non-renewable resources of energy with a limited stock of reserves and fuel import dependence, alternative fuels represent a compelling substitute to fossil fuels, notably in countries lacking in conventional fuels resources.

Moreover, using and re-using a variety of waste available locally, namely, bio-waste, can contribute to streamlined WM support in energy systems transformation [8].

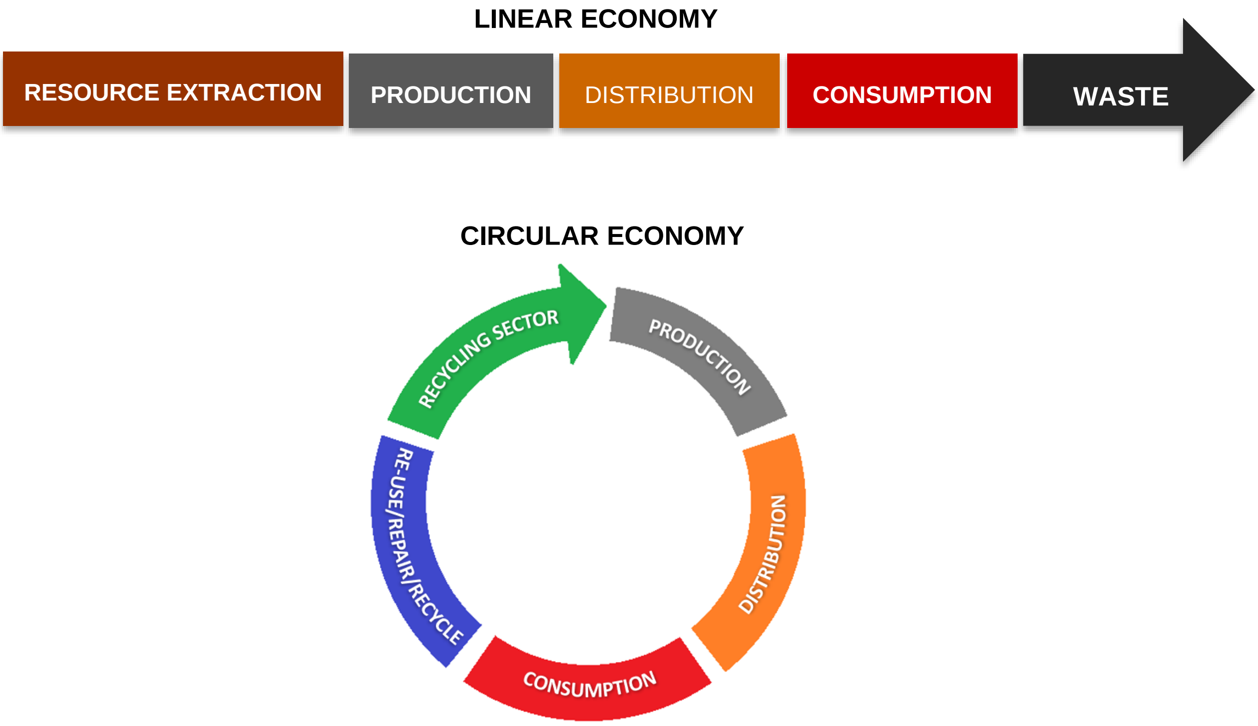

Fig. 1.1 Linear vs. circular economy.

Bio-waste management and utilization are necessary to develop efficient conversion technologies of waste disposal and energy recovery. On top of covering local energy needs, bio-waste can additionally mitigate concerns of material shortage. The expanding economic growth and equivalent consumption of resources over the previous century caused (material and energy) reliance [9] and indicated difficulties with waste management.

Worldwide, 2,01 billion tons of MSW is generated per year, of which around 33% is not handled in an environmentally harmless approach [10]. Globally, waste generation averages 0,74 kilograms per capita per day, although differ broadly, from 0,11 to 4,54. In the outlook, worldwide waste production is predicted to increase to 3,4 billion tons by 2050, beyond double population expansion at the same time. In general, a positive correlation occurs when it comes to waste creation and level of income. In high-income countries, daily generated waste per capita is predicted to expand by 19% by 2050, whereas in low- and middle-income countries, projections show an increase of 40% or higher. At first, the generation of waste declines at the bottom levels of income then expands at a faster pace for gradual income development at low-income grade compared to high-income grade.

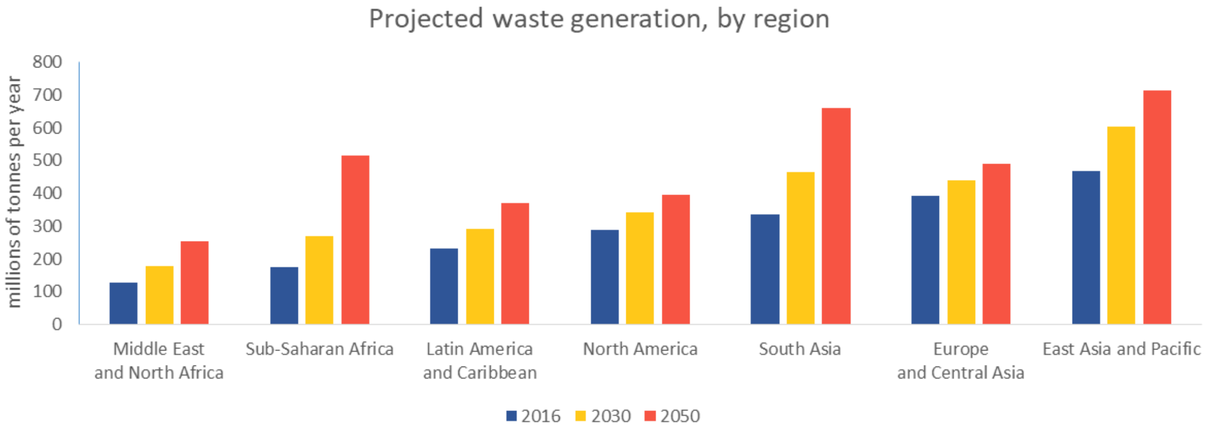

Fig. 1.2 Projected waste generation, by region (millions of tons per year) [10].

The overall volume of waste produced by low-income countries is forecasted to triple by 2050, Most of the world's waste is generated in East Asia and Pacific (EAP) region, at 23%, where the least producing region, the Africa, East Mediterranean (AEM), contributes to 6% production in absolute terms. Nevertheless, the most quickly developing areas are South Asia, Sub-Saharan Africa (SSA), and AEM (Fig. 1.2), which, by 2050, will increase waste generation more than three, two, and two times respectively. In these areas, over half of the waste is nowadays openly thrown away, and the direction of waste increase will have vast entanglements both for the environment and health, as well as welfare, thus compelling necessary action [10].

Components of the waste differ over the region's income levels, indicating a variety of feedstock usage. High-income nations are responsible for generating comparatively less food-related and green waste, at 32% of overall waste, and generate a higher amount of dry waste available for recovery, together with plastic, paper and cardboard, metal, glass, and other which are responsible for 51% of waste. Countries classified as middle- and low-income generate 53% and 57% of food-based and green waste, respectively, with the part of organic waste rising as economic development stage decline. In low-income countries, fractions of waste that could be reused and reprocessed include only 20% of the generated waste. Across regions, diversity within the waste streams does not vary beyond those based on income. Roughly 50% or more of organic waste is generated in all areas, except for Europe and Central areas of Asia (ECA) and North America (NAM), which, in general, produce higher shares of dry waste [10].

Relevant and strictly associated with anthropological activities is additionally the generation of biodegradable wastes or bio-wastes. The European Commission has suggested incorporating "garden and park waste, food processing and kitchen waste from households, restaurants, caterers, and retail premises, and food plants [11]" as fractions of bio-waste. On a more comprehensive basis, the literature extends the range of bio-waste to "residential and sewage wastes, manure, Food Wastes (FWs), and residues from forestry, agriculture, and fisheries" [12]. Whichever the categorization, bio-wastes outline an enormous quantity of organic and inorganic material: the World Bank has evaluated that by 2025, MSW (only a fraction of bio-waste) of the municipal areas globally may attain 2,2 billion tons per year, and rates of waste generation are likely to double over the next two decades in developing countries [13].

The most well-known means of bio-waste disposal involve microbial decomposition under both aerobic and anaerobic conditions, thermal degradation, and dispatch to landfill. In the last few years, the possibilities of bio-waste application have gained progressing recognition in academic and industrial areas intending to identify approaches to convert low-value waste as a source of energy, and concurrently, induce the development of technologies and business models based on waste-to-value industries. Food-derived waste, pig bristles, cattle manure, and household waste are gaining more recognition as model cases of bio-waste. The immense generation, widespread presence, and chemical affluence of before-mentioned residues are promoting their valorisation, one of the most significant perspectives for both an efficient reduction of the environmental implications of bio-waste and financial profit.

1.3 Motivation and Contents

This Master's thesis was motivated in order to research economic opportunities for investment in markets where energy costs and waste disposal costs are relatively high and where valorisation of bio-waste could be introduced. The difficulty of locating the innovative sources of significant inputs and forming valuable raw materials to produce valuable commodities from biowaste utilisation and valorisation is the interest of various regions worldwide.

Nonetheless, this scale research was not yet conducted, including biowaste administration practices differing across rural and urban areas of three world regions. In the study for proposals to this significant challenge, this works' method tested the valorisation methods at three different locations seeking a replicable technology which can help utilise biowaste from any area and which acknowledges the investigation of diverse scenarios.

To achieve this aim, several topics were investigated, including energy resources, means of energy conversion, energy transportation and consumption in two different regions - domestic use of micro bio-digester in French Guiana, and application of WtE systems in the agricultural industry of Indonesia. Technological features and local constraints of the territories were investigated and analysed with two approaches:

1. Technological Perspective
    - Literature review on the local situation in bio-waste valorisation for these different regions,
    - Study on the variety of bio-wastes available by countries and by activities,
    - Benchmark of adapted technologies for waste valorisation in these countries.

2. Business Perspective
    - Market analysis for the different solution of bioenergy from stove to electricity production,
    - Estimation of the payback time based on different study cases,

- Definition of business models adopted in Africa, South Asia, and French Oversea Territories context

This work involved research on internal and external sources of the European Institute for Energy Research (EIFER) as well as exchanges within the Institute, other R&D centres, and business units. The collected materials allowed for the preparation of an extensive literature outline, describing in detail the background, achievements to date, and opportunities used in the development of biowaste valorisation technologies.

1.4 Problem formulation

This research combines technical and economic evaluation of various WtE systems for bio-waste valorisation and pre-feasibility studies. Those systems are characterized by different unit sizes, varying technologies, distinct economic environments, and diverse actors involved (household, industry, and regional authorities).

The first case is the evaluation of most suitable biogas digester for remote, rural areas of Amazon French Guiana, taking into consideration regional and climate characteristics. Moreover, research should find the appropriate size of the digester and the number of family members able to offset LNG utilisation used for cooking through the valorisation of household organic waste based on implemented bio-waste feedstock and aim to examine the energy relationship of substituting LPG and solid, traditional bio-waste by biogas for cooking. Results of the study should allow to duplicate the project in various locations and settings.

The second, and the last case of bio-waste valorisation exercised in this study, is to identify an agro-industry based in Indonesia which could be able to self-sustain electricity generation from production waste of this industry. The exercise should contain a technical-economic analysis which will indicate the feasibility of such a project.

Due to a termination of cooperation with Ghanaian stakeholders the third project was not assessed from one point on and therefore methodology and calculations were not evaluated for this region and part of the project. The aim of it was to find the right size of neighbourhood or district which can self-sustain communal parts in electricity generation. The research was planned to find a suitable technology for waste valorisation, define required actors, and conduct necessary calculations for a pre-feasibility study. This has not been achieved. Nevertheless, the collected materials, theoretical evaluation and recommendations were included in Annex C of this work.

1.5 Thesis outline

This thesis is composed of five chapters and three annexes:

- Chapter 1 – Introduction (6 pages)
    - 1.1 Overview
    - 1.2 Background
    - 1.3 Motivation and contents
    - 1.4 Problem formulation
    - 1.5 Thesis outline
- Chapter 2 – Literature Review (13 pages)
    - 2.1 – Biogas for household supply in rural areas
    - 2.3 – Potential of agro-industry for locally produced bio-waste energy
- Chapter 3 – Methodology (7 pages)
    - 3.1 – Digester evaluation methods
    - 3.2 – Rice husk evaluation analysis
- Chapter 4 – Analysis of results (13 pages)
    - 4.1 – Investigation on biogas digesters
    - 4.2 – Rice husk valorisation analysis
- Chapter 5 – Conclusions and recommendations (3 pages)

Annex A - Biogas digesters available on the market

Annex B - Business Model

Annex C - Biogas-based electricity generation from Municipal Solid Waste

Chapter 2

Waste-to-energy as a source of alternative and sustainable energy generation in terms of its techno-economic viability.

This chapter provides an overview of reviewed possibilities of bio-waste valorisation in three specific locations, mainly focusing on the capacity aspects of the available bio-waste in those areas.

2.1 Biogas household supply in rural areas of French Guiana

WtE technologies allow for incorporating the encouragement of presenting a synergistic connection linking industry and numerous levels of government to divert organic wastes like wastewater sludge, agricultural and livestock waste, FW, and MSW for propitious energy utilization while overcoming the challenge related to the volume of waste disposed to the environment [15]. The WtE strategy aims at delivering practical application of waste resources, based on a methodology which likely eradicates, or at least significantly decreases harmful impacts on public health, safety, welfare, and the environment [16]. Additionally, it should contribute to sustainability components and implement a net positive energy result. A vital factor when it comes to the WtE landscape is the hierarchy of the waste management process that commonly represents a prioritization in the waste management treatment, which should be mainly focused on waste minimization and diversion, and then, only as a last alternative, waste disposal.

WtE applies to a wide range of treatment technologies that are converting waste to biofuels, heat, electricity, or other utilizable materials. In reference to its energy conversion methods, WtE classification is arranged into four divisions: biochemical, thermal, thermochemical, and thermo-mechanical. In the waste management hierarchy, additional categorization applies to disposal, other recovery or, recycling operations based on created energy products and recovery levels [17].

The following chapter presents a resource assessment of selected WtE feedstocks based on scale, size, and applicability for including production of energy potential and the general characteristic, technical approach, previous experience, and similar projects references.

2.1.1 Bio-waste utilization in French Guiana

Remote areas, such as the French Guiana tropical rainforest, which covers around 90% [18] of the country's area, qualify as territories difficult and expensive to connect to the utility network. Those areas are challenging for the supply and transport of needed fuels and fertilizers, which is significantly hindered due to the lack of required infrastructure. A promising solution to this problem could be the application of renewable energies produced in a decentralised way. Utilization of bio-wastes, as one of the abundantly available resources in those areas, could contribute to the process of recovery, nutrients recycle, and biogas production, which ultimately solves the availability challenge of necessary energy supply. Biogas digesters can be used in rural areas to meet energy demands and contribute to clean and sustainable energy generation under responsible consumption and production.

The French Guiana region has several demanding characteristics. As an "island territory" located far away from mainland France, it is related to the European Union, and consequently, French Guiana is bound to consume fuels within European standards, which makes it challenging to import fuels from neighbouring countries. These restrictions lead to the difficulties associated with the logistics of supplying this region with fuels and fertilizers, thereby affecting its limited availability.

Before both fuel and fertilizer reach rural areas, their final cost is much higher than the original amount due to related price of handling and transportation, which pressures people to look for alternative resources [19]. Therefore, numerous rural populations are bound to depend on traditional energy sources suchlike fuelwood, animal dung, crop waste, and paraffin. These conventional methods are often costly and time-consuming [20]. Cooking and meal preparation are estimated to amount to 90% of the consumed energy in households in remote areas [21].

As a fuel, biogas can be a replacement for fuelwood and animal dung, meeting the energy demands of the rural community [22, 23]. As a renewable fuel, biogas can substitute natural gas and liquefied petroleum gas (LPG) [24]. Various models help to estimate the energy contained in diverse energy sources, which consider water boiling (WBT) and controlled cooking test, as well as kitchen performance test [25]. The chemical energy contained in 1m^3 of refined biogas is equivalent to 1,1 litre of gasoline, 1,7 litre of bioethanol, or 0,97 m^3 of natural gas [24]. The use of biogas in rural and municipal waste treatment is widely disseminated. Nevertheless, it poses a hurdle for designers and specialists to construct a capable domestic digester with the accessible materials, preferably in the region, simultaneously considering local conditions and economic constraints. Even though various digester models have been built, further research and recognition are required to meet the growing needs and circumstances [26].

Establishing a suitable model of the digester for household use is usually challenging. The form of the digesters varies concerning the geographic location, provision of the substrate, and climate conditions. For example, the structure of a digester operated in mountain regions is adapted to bear scarcer gas volume to evade gas losses. For tropical areas, it is favoured to place subsurface digesters due to the presence of geothermal energy. From so far developed digesters, the fixed dome model, widely spread in China, and the floating drum digester (popular in India) has remained into operate to this day. For some time, plug flow digesters have been earning recognition because of the portability and effortless operation [27].

Contrary to other renewable fuels, like biodiesel or bioethanol, biogas generation is moderately easy and can work under undemanding conditions [28,29]. Cow dung is a possible feedstock for biogas production, commonly perceived solely as floor polish or field fertilizer for hundreds of years. Biogas, as rural fuel, is sustainable, inexpensive, and does not present a harmful effect on people’s well-being or the environment if adequately managed [30]. Complex structure, elaborate mechanism operation, significant investment cost, and laborious maintenance have urged farmers to comprise more affordable and plainer anaerobic systems [31].

In China, where biogas digesters are widely popular in rural areas, they are present in over 30 million households, further 3,8 million in India, and around 0,3 million in Southeast Asia [32–33]. China has been investing in biogas development very expeditiously. To date, 80 million of its households are presumed to own biogas digesters servicing 300 million citizens [34]. Moreover, the most extensive renewable energy programs are taking place in India, where various scales and levels of technologies are being applied, among which approach to promoting biogas plants is considerably widespread [35]. Related trends can be noticed in other Asian countries, for example, in Vietnam where Dutch NGO, SNV Netherlands Development Organisation, has installed over 20,000 plants [36]. The development level of family-size biogas digesters is deficient throughout African countries [37].

Additionally, insufficient technical properties of structure and utilized materials, unskilled constructors, and inadequate understanding of the system in the application are a few of the causes accountable for lack of success in this area [34]. Even though potential demand is particularly significant in Africa, technology is immature at this stage, amidst many regions, struggling to satisfy their energy demands [38].

2.1.2 Environmental aims

In rural areas, households with the lowest income depend on commonly used fuels, namely fuelwood and dried manure, to serve everyday needs for heating and cooking purposes. Conversely, LPG, commonly used in the form of propane gas, is utilized by small-scale farmers, for which this form of fuel is more available and less expensive. Most notably, private enterprises launched large-scale subsidies promoting the usage of this fuel in rural areas, therefore developing their business market [40]. At present, the application of LPG stands for approximately 40% of the energy mix of supplied fuels for heating and cooking in rural areas of French Guiana (Global Alliance for Clean Cookstoves, 2012). Nevertheless, there are limitations to obtaining the aforementioned energy fuel, like price (on average US$ 50 monthly), transportation cost from municipal to rural areas (on average US$ 25 per month), as well as a hazard in propane container management [41].

Furthermore, in small-scale Amazon farms, cattle waste (i.e., cow dung) is not adequately managed, which impacts the environment through odorous scents, greenhouse gas (GHG) emissions, and pollution of groundwater and soil. Generally, manure, having the possibility to be converted into bio-fertilizer, is accumulated lacking any additional processing. Improperly managed manure induces not only dangerous pollution but also causes diseases impacting animals and humans originated from pathogen microorganisms included in the waste [42].

From this perspective, affordable biogas plants seem like the right candidate in the context of diminishing environmental impacts while elevating the living conditions of rural households. Low-cost digesters acknowledged as a clean, reliable and sustainable technology, may support small-scale farmers in dealing with household and livestock waste in an environment-friendly way, and providing a source of energy and fertilizer simultaneously. (i.e., by providing biogas) [43].

The utilization of biogas leads to a reduction of eutrophication, enhanced usage of harvested crop nutrients [44]. By reducing the day-to-day tasks of fuelwood collection, biogas technology decreases, if not eradicates, labour work for women [45]. Moreover, biogas is generated, in principle, from raw materials, available locally, and provided in manageable, controllable, and usable amounts. In summary, biogas energy production modifies an expensive obstacle into a profitable solution.

The combustion of biogas does not emit PM and based on that reason is believed to be a clean-burning gas, although containing minor levels of poisonous hydrogen sulphide (H_2S). The evaluations of indoor air quality [46] show that H_2S levels remain under detectable limits (<2ppm) after five-hour biogas combustion. The level of PM emissions was considerably reduced in a scenario in which biogas was utilized instead of fuel wood [47]. Apart from air quality improvement, the change of fuelwood with biogas has socio-economic gains because local inhabitants (mostly women and children) use less time gathering wood and longer time pursuing other actions like education and leisure.

Several researches evaluated the environmental gains of low-cost digesters applied in remote areas of Peru, Colombia, China, India, and Vietnam. Those investigations showed that low-cost digesters resulted in environmental gains by decreasing GHG emissions and limiting soil and water contamination [48, 49].

2.1.3 Micro-scale prefabricated biogas digesters

Biogas digesters are used to produce biogas through the process of the anaerobic fermentation of organic matter in the absence of oxygen [50]. Various factors can influence the anaerobic digestion (AD) process, such as temperature, Hydraulic Retention Time (HRT), and digestate composition; different types of feedstock will decompose at different rates, and consequently, generate different quantities of methane. Nevertheless, the mixing of various substrates enhances methane production and decreases life cycle costs [51].

Fig. 2. 1 - Horizontal polyethylene-based tubular [56].

At present, the most widespread kind of small-scale digester is the Taiwanese design, which involves a horizontal polyethylene-based tubular bag (Fig. 2.1) [52, 53]. This scheme has presented propitious outcomes in research in Costa Rica for a combination of swine waste and cooking oil [46] and the Andes of Peru for cattle manure [54]. This model of the digester is moderately low-priced and simple in installation, but prolonged sun exposure can decrease the elasticity of the polyethylene bag, which over time, can cause leakage [46, 55]. The research opposing the fixed dome digester (Chinese type) with the tubular bag digester (Taiwanese type) [56] assumed that the significant disadvantage in terms of utilizing the fixed-dome digester is the moderately large capital cost (CAPEX) and complicated construction. Whereas the tubular bag digester is, in general, more affordable and simpler in installation, it could acquire substantially more maintenance costs with periodical replacing of the polyethylene container [56].

Experience in other countries, e.g., Indonesia, presents the installation of bio-digesters with support from local governments in remote villages. In those cases, digesters were built based on the Chinese design - concrete construction in an upright fixed-dome arrangement [57]. Based on the analysis of conducted projects, the rural populations soon abandoned various digesters as a result of incorrect construction, insignificant institutional supervision, and inadequate preparation of the potential operators. Certainly, the above examples are just some of the various obstacles limiting the spread of biogas technology in rural areas. Southeast Asian countries are supervising the employment of biogas systems in rural communities with above 40 million biodigesters placed [54]; nonetheless, these applications needed over half of the century of continued governmental support [57, 55].

In opposition to brick-and-cement digesters constructed on-site, a prefabricated biogas digester (PBD), e.g. Fig. 2.2, is manufactured offsite, applying materials with specific physical characteristics.

Prefabricated or available commercially digesters are categorized as fiber-reinforced plastic (FRP) digesters, plastic soft (PS) digesters, and plastic hard (PH) digesters. FRP digesters are indicative of PBDs, as they penetrated the market right at the start of their expansion. PS digesters are commonly called bag digesters in several countries as they resemble big smooth bags. PH digesters are typically solid, hard digesters. All of the above digesters differ in the type and chemical composition of the plastic from which they are made and are therefore equipped with various physical properties [58].

Fig. 2. 2 – A complete PBD produced in China [146]

With the development of the biogas digesters commercialization, the prefabricated and self-assembled model was created. This kind of digester is a disassemblable system that is mostly accustomed to handling green and kitchen waste. A standard prefabricated and on-site assembled digester is shown in Fig. 2.3.

Along with the modification of feedstock for AD and with the deficiency of animal manure in rural areas, prefabricated and assembled digesters are foreseen as an advantageous technological path for the use and processing of some organic waste [59].

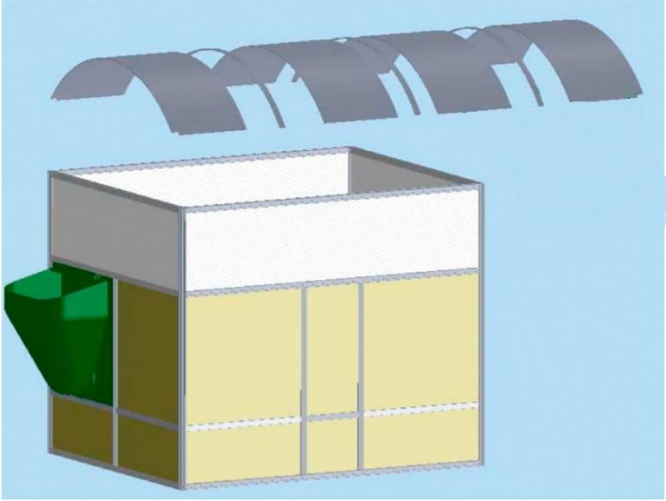

Fig. 2. 3 Model of portable bio-digester (based on [60]).

PBDs were created once the biogas process implementers realized the limitations of digesters constructed onsite, and weaknesses of their brick- and cement-based structure. A distinct benefit of PBDs over brick digesters is the perpetual quality check at the manufacturing facility. PBDs are able to bear adequate mechanical strength with proper airtightness, as well as extended service life. They usually present an excellent insulation effect to keep enduringly constant internal temperature. Due to their lightweight, PBDs can be easily shipped. No prolonged assembly periods are needed since they are manufactured off site beforehand and could be deposited until handled. A qualitative connection between PBDs and OCDs is shown in Table 1. Usually PBDs are more expensive than OCDs [61]; FRP digesters cost is higher than PH and PS digesters.

In general, the important aspect of prefabricated digesters is the self-made/self-assembled characteristic, simpler and cheaper construction than masonry digester, and longer lifetime than plastic bag.

2.1.4 Evaluation of biogas application methods

Biogas has several energy applications, which depend upon the characteristics of the biogas origin and the on-site energy demand. In rural areas, it is generally utilized in cooking stoves, heaters, lamps, refrigerators, and engines.

The effectiveness of energy conversion when adopting biogas is ca. 55 % in cooking stoves, 30 % in motors, but barely 3 % in light lamps. In comparison with a kerosene lamp, a biogas lamp generates half of the energy. The most productive method of utilizing biogas is seen in a combination of heat and power, where 88 % of performance efficiency can be attained. Nonetheless, this possibility remains feasible for installations with a large capacity where the exhausted heat is used again [62].

Table 1 Comparison of digesters quality.

	Digester			
	FRP	**PS**	**PH**	**Brick**
Expense	Significant	Low	Average	Average
Work labour	Low	Low	Low	Significant
Prefabricated	Yes	Yes	Yes	No
Maintenance	Low	Low	Low	High
Lifespan	Long	Short	Long	Average

FRP - Fiber-reinforced plastic; PS – Plastic soft; PH – Plastic hard

〉 Cooking and lighting

People living in rural regions primarily depend on traditional bio-waste to satisfy their demand for energy [63], with cooking being one of the essential energy-consuming end-user services. The application of bio-waste would not be of concern if practised in a sustainable approach employing efficient and effective conversion technologies. Nevertheless, if applied unsustainably and ineffectively, it can have opposing consequences on health and well-being, environment, and prosperity. Yearly over one million people die because of the indoor air pollution caused by the use of traditional bio-waste [64]. Rural areas inhabitants spend their valuable time to collect and gather wood for cooking which might be contrarily applied to get an education or practice income-generating actions. The unsustainable handling of wood may additionally lead to forest damage [65]. The most commonly used fuel in those areas is LPG. This work proposes to examine the energy relationship of substituting LPG and solid, traditional bio-waste by biogas. LPG is imported from other countries or mainland France; therefore, the cost of delivered fuel is substantial [66-67].

Biogas generated from the domestic digesters is mostly applied for cooking [68]. The volume of biogas utilized for cooking varies typically within the range of 30 and 45 cubic meters per month. This amount can be linked with other ordinarily utilized fuels, namely, kerosene, where the usage is 15 - 20 litres, and from 11 to 15 kg of LPG per month, respectively. The equivalent of energy was approximately 315, 215, and 165 kWh for biogas, kerosene, and LPG, respectively [66-68]. The excess biogas in the household digester could be utilized for lighting [69].

2.2 Potential of agro-industry for locally produced bio-waste energy

There are considerable volumes of residues related to agricultural operation and processing industries. Bio-waste residue from agroindustry used for energy generation is among the main interest domains of renewable sources of energy in various countries globally. A substantial volume of bio-waste residue is created from agriculture. Nevertheless, the bio-waste waste is the disseminated asset with variety in time-and-place supply and energy potential properties. Bio-waste waste follows harvesting of primary crops like straws, Empty Fruit Bunches (EFBs), stems, cobs, leaves, coats, husks, etc. This waste can be utilized as a feedstock for energy generation, given that it satisfies the standards of abundant supply and local accessibility on a recurrent and continuous basis. In Indonesia, agricultural waste is in abundance
as a wide variety of crops is cultivated to provide food for 77% of its population [105]. Compared to conventional fuels, with limited availability, agricultural wastes are not only plentiful but also renewable and sustainable. The application of various residues is often uneconomical due to the enormous investment cost necessary for harvesting, transporting, and storage. Nevertheless, certain bio-waste residues are centralized in a particular area, where energy demand occurs as well —sectors with the most significant potential stem from palm oil, rice, and sugar cane industries.

2.2.1 Power market background and bio-waste resource potential in Indonesia

Even though Indonesia produces plentiful bio-waste feedstock, which might be utilized to generate renewable energy, the ongoing power generation is primarily based on conventional fuels such as crude oil, natural gas, and coal.

The economic influences are dominating this narrative supported by the environmental impacts of non-renewable fuel consumption. The national energy demand reveals the growth of 7-10% per year [106], which, combined with unstable commodities markets, remains a costly concern for the country administration. To ensure a basic level of energy security, power generation is heavily subsidized (in 2018, about 98,51% of the population had access to electricity [107]. Above mentioned determinants challenge Indonesian administration to locate diverse sources of power that enable the cost-efficient delivery of electricity.

The Indonesian Government proposed certain policy measures to enhance private business financing to renewable energies to satisfy the increasing demand and improve the electrification system of the country. The primary means in this array of actions is the introduction of feed-in tariff compensating electricity generation of renewable origin, sold to PLN (Indonesian government-owned electricity distribution corporation). For plants using bio-waste and biogas (<10 MW installed capacity), regulations anticipate 975 - 1772,50 IDR/kWh rate [108], conditional to the plant's location and proximity to the power network.

Residues from agroindustry are a favourable source of self-produced energy for the production and processing sectors in rural Indonesia. A decentralized energy system relying on crop residues can support establishing novel agro-based business motions in rural zones, consequently forming large-scale employment. Recognized as CO2 neutral, the before-mentioned systems will not contribute to environmental pollution.

A large volume of bio-waste waste in Indonesia is produced as a residue from the palm oil extracting process, e.g., EFB, fiber, shell, and Palm Oil Mill Effluent (POME) (Table 3). Attained bio-waste residue might be adopted as combustible in the furnace or be altered to biofertilizer. Palm oil mills run the co-generation system to generate power and produce steam, needed for the palm oil-producing, applying bio-waste (in the solid form) as the primary energy origin. Evaluating the power generation's ability concerning the mass and energy balance revealed that the bio-waste handled in the processing plants used as a feedstock to generate electricity might potentially cover more than the process requires [109]. The study on palm oil residue combustion characteristics (i.e. kernel shell, fiber, empty fruit bunches), as well as coal-bio-waste blends used in co-firing, reported that is likely to decrease coal consumption [110]. The necessity for the advancement of valuable products from bio-waste residue and the development of palm oil mills toward bio-refineries was highlighted in numerous research [109, 111-112].

Indonesia is the third biggest rice producer globally, right after China and India, which brings the immense potential for energy production using this renewable source [113]. Nevertheless, the country continues to face shortages of power, with the electrification ratio indicating yet not full coverage, primarily outside regions other than Java. Many villages in rural areas are not connected to the grid and short on the power supply; on the other hand, urban areas are experiencing recurrent blackouts caused by inadequate power generation. The operating power plants are incapable of assisting society's needs and industrial development. Over half of Indonesia's demand is covered by coal, which domestic reserves are still abundant; nevertheless, they most likely are out in a short time on a large-scale. Besides, coal harms the environment, from the point of mining to combustion [114]. Appropriating rice husks as fuel is an innovative yet widely discussed idea. At present, rice husk is usually disposed of as waste, polluting the environment simultaneously. An interesting choice to subdue these difficulties is to fully take advantage of the rice husk fuel potential in industry and power plants. Consequently, it can degrade the coal application and diminish environmental impact.

The rice husk is the coating of the seed or grain of rice and takes the form of a hull or shell. It accounts for 15-34% of the rice paddy collected weight, varying due to the rice paddy type, and it typically signifies 20% of the rice paddy given on weight. The typical lower heating value of this product is around 13,5-14,8 MJ/kg [112]. It could be indicated that the lower heating value of rice husk represents around a third of furnace oil, half as thermal coal, and similar values to wood shavings, lignite, and turf.

The material is also sustainable and does not remain a source of pollution due to minimal sulphur and heavy metal content.

Table 2 Palm oil mil residues and theoretical electricity generation [109].

	Quantity of residues				
	Fresh Fruit Bunch [%]	**Mass [ton]**	**Volume [m^3]**	**Theoretical electricity generation [GWh_e]**	**Type of process**
POME	58		58 053 006	1 171	Biogas combustion
EFB	21	21 019 834		26 786	Material combustion
Shell	6,5	6 506 739		115 874	Material combustion
Fiber	15	15 014 460			Material combustion

POME - Palm Oil Mil Effluent; EFB – Empty Fruit Bunch

It is not economically feasible to transfer rice husks out of the original milling location to the utilization area that is distant from the mill as a result of inherently low energy density. On the other hand, it could be attainable to collect rice husks from various mills located in the area in certain regions. Rice husk moved over a small distance can be competing with imported distillates, which must be transported across a considerable distance inside the country. Consequently, if a suitable system is obtainable, the rice husk can be altered to a valuable energy form to satisfy the thermal and mechanical conditions to process the paddy as well as the power demand in the neighbouring district.

Indonesia has a dominant agricultural sector and, consequently, an enormous capability to apply the agro-industry residues as a commodity for electric energy generation. The capacity for applying bio-waste for power production is assessed at about 50 GW. At present, with the total installed capacity of 1,84 GW, there is still considerable scope for further expansion.

2.2.2 Environmental impact and feedstock selection

As a world's front producer of palm oil, Indonesia provides nearly 50% of the product worldwide, and self-drives expanded palm oil use by implementing national biofuel policies. Though the oil palm has high efficiency as a crop, there are critical environmental and public impacts of the promptly developing industry [115].

Considering that the comprehensive land area used for cultivation and farming is restrained, the developing market for palm oil leads to the increase of this production toward other agricultural lands and primary tropical forests. Traditional palm oil development, which frequently replenishes tropical forests with monocropping operations, drains biodiversity, damages the old-growth rainforest, and induces air pollution [116].

Southeast Asia covers four of the globe's distinguished "biodiversity hot-spots," each representing exceptional geological records and wildlife. Sadly, tropical forests in Indonesia and neighbouring countries are subject to destruction more rapidly than in different areas worldwide. Around 0,85 Mha of Indonesia's primary forest is lost annually, adding up to 6,8 Mha since the beginning of the century [115]. It considerably surpasses deforestation's degree in Amazon; around 50% of this decline has been assigned to expanding palm oil plantations. The adverse outcomes of this damage to biodiversity are overwhelming, as an individual hectare of primary rainforest in Indonesia shelters over 200 floral species [117].

The change in land use in the tropics estimates for 15-20% of cumulative GHG emissions, thereby addressing it as the second largest GHG origin globally [115]. The palm oil industry's carbon footprint owns two constituents: emissions from deforestation and emissions from palm oil processing. Transforming rainforest into oil palm farms leads to the damage of substantial quantities of carbon from biota and the harmed soil. Notably, the dewatering of peat swamp forests for oil palm set up is correlated with remarkable CO2 emissions when the organic material amassed over millions of years is granted to decay [117]. Due to significant emissions incorporated into palm oil spread, the carbon preservations are counterbalanced by the losses. Estimates indicate that to balance the loss of carbon from the rising and manufactured product, it could take from 75 to 600 years for the CO2 gains of diesel offset by biofuel originating from palm oil [118]. Research suggests that agricultural bio-waste bears a lower environmental impact in comparison to fossil fuels due to zero net CO2 emissions of biomass by photosynthesis [120, 121]. Simply put, the CO2 obtained during the plant's life cycle is used as an energy reservoir. Hence, utilizing palm oil waste or rice husk to produce energy is a practical possibility to alleviate environmental impacts with various technologies [122]. Several studies have reported specific GHG emission measures for incineration of diverse fuels and heating values of individual fuel, as shown in Table 4.

Table 3 GHG emissions of selected fuels [118].

Fuel	**CO$_2$ emissions** $\left[\frac{\text{kg CO}_2\text{eq}}{\text{kg fuel}}\right]$	**Calorific value** $\left[\frac{\text{MJ}}{\text{kg fuel}}\right]$	$\left[\frac{\textbf{kg CO}_2\textbf{eq}}{\textbf{MJ}}\right]$
Coal	2,15	20,6	0,104
Rice husk	0,11	14,1	0,008
Diesel	3,25	42,9	0,076

The analysed life cycle assessment (LCA) studies [113-114, 119-122] to acquire energy from rice wastes using thermochemical conversion processes have concentrated on detailing the GHG emissions. The majority of studies eliminated the paddy cultivation (crop field) out of the system environment, even though it generally designates the most 40% impact on the environment [123]. The generated emissions arise mostly on account of fertilizer utilization and fossil fuel burning to manage agricultural equipment; their share varies between 70% and 90% [124]. Hence, a substantial difference is provided in the study, decreasing the evaluation of the effects on the environment throughout the life cycle of generating power from rice bio-waste.

Besides, certain aims and interim involvements were adapted to decrease GHG emissions as a means to reduce the climate crisis. Furthermore, developing nations which concentrate the most significant rice production worldwide, are presently bound to respect the GHG emissions mitigation goals employed by the Paris Agreement [3]. Even though this setting gives priority to the evaluation and reduction of GHG emissions, it is crucial to recognize different environmental impacts like land employment or water management, which could harm the environment.

2.2.3 Methods of bio-waste valorisation

There are certain technologies for recovering energy from the rice husk, in particular, thermo-chemical processes: combustion, gasification, and pyrolysis. In the presented literature review, the two former technologies are briefly described and reviewed due to their popularity and a vast number of studies conducted worldwide. In contrast, fast pyrolysis has still much ongoing development as a modern, promising technology [125].

In the process of direct combustion, rice husk is used in a steam boiler in the combustion chamber's air environment. Heat and power can be synchronously produced (co-generation) through turbine utilization. In general, bio-waste combustion conversion technologies can be sorted under the fixed bed and fluidized bed combustion systems. Other scientific works [126] estimated the economic viability of introducing steam power plants installed in the rice mills using a comparison of two systems: gasifier-internal combustion engine and boiler-turbine. The outcomes indicate that both considered arrangements are economically viable to satisfy energy demand.

The economic model was created [127] to determine the internal rate of return (IRR) on the invested capital of steam engines utilizing rice husk in rice mills. The findings indicate that the solution is profitable to introduce steam power engines in rice mills in which capacity falls between 40 and 130 tons [126]. In subsequent analysis, the authors included the profits from selling the surplus of electricity to the grid through a feed-in tariff. The research illustrated that the embodiment of a generator connected to the grid with a steam engine fuelled by rice husk represents a beneficial effect on rice mills' budget execution with an estimated capacity of 120 tons per day [127].

Until now, the process of using rice bio-waste to generate heat and power has been adequately determined. In the Southeast Asia region solely, rice husk is utilized as co-generation fuel in, to date, 46 projects [128]. Several producers favour using rice husk only as fuel, because of the implied earnings formed through sales of rice husk ash containing silica.

Gasification can be identified as the process of bio-waste conversion or every solid fuel to a gaseous fuel through partial oxidation in high temperatures [129]. The most popular categorization of gasifier types applies to the bed type. Among the fixed bed gasifiers, the flow of the bio-waste takes place solely by gravitation. Conversely, in fluidized bed gasifiers, fuel is held suspended by a vivid oxidant medium flow, usually air, oxygen, or steam.

Through a gasification process, the rice husk is instantly reformed into synthesis gas (syngas) inside the gasifier in conditions of a fixed volume of air. The utilization of syngas can occur in internal combustion engines to generate heat, or else in co-generation systems to generate heat and power.

There are examples in the literature of determining the unit price of power by adopting a rice husk gasifier-based power generation system and evaluating its financial viability with utility suppliers versus diesel-generated electricity [130]. Another one [131] discusses the feasibility of rural electrification by introducing power generation via rice husk gasification. The outcomes imply that despite high energy potential in bio-waste like rice husks, to satisfy an agricultural residue gasification system over time might involve tree plantation to ensure ample assets [131]. These studies suggest that the viability of certain large-scale projects depends mainly on the plant location, which influences the resource provision and the fetched logistic fees of the chosen bio-waste feedstock.

At the industrial scale, gasification of agricultural wastes and electricity generation systems had been firmly established. Some of the commercial systems and solutions capacities range from 200 to 10,000 kW.

The financial viability of a gasification power plant depends on various factors, primarily the capital expenses of the equipment (i.e., gasifier, engine-generator sets, civil and construction works, and local distribution network (LDN)), particular fuel usage, the net capacity factor, the serviceable lifespan of the equipment and price of fuel. Evaluation of the financial viability can be indicated by several factors, the commonly adopted are, i.e., the levelized cost of energy (LCOE) and the break-even analysis implications (such as estimated cost of diesel or the distance from nearest transmission lines), as well as IRR and the Net Present Value (NPV) [131,132].

Chapter 3

Methodology

This chapter illustrates the processes and hypotheses applied in this thesis. The methodology is separated into a couple of parts: establishing technology used to valorise bio-waste, the estimation of the potential substrate and rice husk, the estimation of biogas, syngas production and electricity generation, the analysis of the economics of those systems, as well as environmental and social benefits. Each section presents the explanation of the applied approaches for preparing the investigation. The core approaches and methods applied are literature review, multi-criteria analysis, NPV, IRR, payback time, and LCOE. These approaches and methods are outlined in the subsequent part.

The presented Chapter was prepared through a literature review based on scientific articles, documentation from previous EIFER bio-waste-based projects, and additional sources relating to small-scale biodigesters and rice husk power generation in various countries. These constituents were assessed and evaluated, acknowledging features of undertaken projects.

Firstly, the methods used to determine the appropriate type of biogas digester, as well as its' size and produced biogas potential, were described. The initial reports adopted in this chapter are records from the EIFER projects concerning biogas production in South America and the Caribbean.

Secondly, the methods used to assess rice husk potential and the components of technical-economic analysis were presented. Methods were adapted from a study on rice husk utilization in Cambodia and India. In order to check the figures, data from the Central Agency on Statistics of Indonesia was used,

5.1 Digester evaluation method

5.1.1 Multi-criteria Analysis

Multi-criteria Analysis (MCA) was applied for the comparison of possible choice of digester.

The MCA method is beneficial in decision-making processes, leaning on evaluating various alternatives under specific standards. It can be applied to identify the most favoured possibility, provide a ranking to the alternatives, or identify satisfactory and unsatisfactory choices.

The total employment of MCA typically involves seven stages [133]:

1. Setting the circumstances of the decision.
2. Identifying the options which will be evaluated.
3. Identifying the aims and models that indicate the significance correlated with the outcomes of individual options.
4. Describing the presumed performance of individual options toward the models. (If the investigation is to involve stages 5 and 6, additionally 'mark' the options, i.e., evaluate the significance correlated with specific option's outcomes.)
5. 'Weighting.' Assigning importance for individual criteria to indicate their dependent weight to the judgment.
6. Consolidating the importance and significance of individual options to determine absolute value.
7. Examining the outcomes.

A characteristic hallmark of the MCA is the performance matrix, or consequence table, where every row represents an option. Every column represents the performance of the options toward every criterion.

The specific performance evaluations frequently have a numerical value but might likewise be displayed as ‘bullet point’ rates, or color-coded [133].

In MCA cases with a limited number of choices, an individual choice evaluated concerning a presented number of criteria, the first stage of reference is primarily the performance matrix. Each of the individual options, for each of the criteria, these performance details require to be gathered.

In a fundamental MCA framework, the performance matrix can be adapted as the final result of the examination. The decision-makers are consequently obliged to evaluate the degree to which the records match their targets in the matrix. Before-mentioned instinctive handling of the information might be rapid and efficient. On the other hand, it might likewise result in the usage of unwarranted presumptions, prompting unreliable classification of options.

A performance matrix is constructed as follows: rows outline the options, whereas columns criteria's performance for all of the options. Table 5 shows an example matrix.

Designations displayed in the performance matrix, represent the criterion's n weight (w_n) and the option's *i* score (s_{in}) respective to the *n*-criterion. Numbers typically demonstrate the performance of individual criteria. More favoured choices score better, whereas less favoured choices score lower on the scale. In effect, scales increasing from 0 to 100 constitute the most often applied form, where 0 denotes an authentic or theoretical least favoured choice, and 100 is affiliated with an authentic or theoretical most favoured choice. Consequently, all choices weighed by the MCA are always in rage 0 and 100 [133].

Table 4 Performance matrix [133]

Criteria	**Criterion 1**	**Criterion 2**	**…**	**Criterion n**
Options	w_1	w_2		w_n
Option 1	s_{11}	s_{12}	…	s_{1n}
Option 2	s_{21}	s_{22}	…	s_{2n}
…	…	…	…	…
Option *i*	s_{i1}	s_{i2}	…	s_{in}

The rates within these intervals can be defined by applying three alternatives, from which only two are described and applied in this thesis.

The first one applies the value function concept, where two extreme rates relate to 0 and 100, Consequently, a linear graph is generated, where values for criteria are represented as follows: the score on the vertical axis and options rate on the horizontal axis. Thereby, all of the scores' values can be instantaneously interpreted from the vertical axis graph.

Another alternative is the direct rating. It is applied if there is no fixed scale of estimation, or in the case, there is no time or means for adopting the criteria. This method can be very inconsistent based on the decision of the reviewer. In the above case, the rates are also awarded on the scale from 0 to 100 [133].

The employment of different methods can obtain outcomes from the MCA. Smooth and sophisticated methods apply for performing an MCA. They rely upon the purposes and the scope of the inquiry. The methods usually include numerical analysis of grading the benchmark per every alternative and weighing the criteria in line with their strength separately from the preference [133].

The method applied in this thesis is based on the linear additive model. Every provided rate is multiplied by the criterion weight. These values are later summed up to achieve an inclusive weighted amount for each of the options. See Equation 1.

The MCA in this thesis aims to recognize which of the bio-waste technologies introduced in Chapter 2, both for biogas production and electricity generation, could adequately satisfy the multi-energy systems' properties. This step is undertaken to determine the design of the techno-economic study. In general, the MCA requires various actors; nevertheless, in this study it will exclusively be prepared relying on the literature review, results from the past analysed projects co-implemented by EIFER, and the author's decision.

$$s_i = \sum_{j=1}^{n} w_j s_j = w_1 s_{i1} + w_2 s_{i2} + \cdots + w_n s_{in}$$

Where: w_n – n-criterion’s weight

s_{in} – score of option i

Equation 1 – Weighted sum of linear model [133]

The choices to be assessed are the three technologies presented in Chapter 2 and more comprehensively described in parts of Chapter 4, i.e., fixed dome digester, floating drum digester, and prefabricated digester.

The conditions for these evaluations are established by the features that can affect the efficiency of the evaluated system recognizing the limitations of the analysed area. The factors to be appraised for the choice of digester are durability, technical expertise and skills, physical construction, and CAPEX.

The outcomes of the investigation are available in Chapter 4.1.

5.1.2 Digester size and biogas potential

The estimation of the biogas production rate per kilogram of a specific process inside the digester fluctuates between different bio-waste materials. Biogas production is influenced by the nature of the feedstock and the abundance of essential components; every feedstock material has a particular fermentation period and volume of biogas produced under normal conditions [56]. Biogas yields of various commonly used materials are presented in Table 6.

The size of a biogas digester is the highest cumulative volume of biogas and bio-slurry which can be contained in the unit. It is described in m^3. The volume of the biogas digester is the highest level of slurry which can behold by the unit, whereas the gas capacity is the maximum volume of gas when the unit is full of slurry. The digester size can also carry a safety factor or a “dead zone volume”, mostly applied to restrict waste congestion on times when biogas generation is greater than usual, or biogas application is abnormally weak [150].

Table 5 Yields of different wet feedstock types [134].

Waste [kg]	**Biogas yield [m^3/kg]**
Wastewater solid fraction	0,11-0,065
Cattle	0,04-0,023
Sheep	0,03
Poultry	0,11-0,065

Assumptions stated below were taken under consideration to estimate the size of the digester and production of biogas:

1. The absolute mass is the bio-waste mass and water mass. It was estimated that for every kilogram of dry waste, 2 kilograms of water are needed.

2. For the household, food cooking and preparation were presumed to occur two times per day. Therefore, half of the biogas produced for one day was obtainable for the duration of one cooking period.

The parameters of each biogas digester's design were attributed to the feedstock type. Two designs were taken into consideration: based on domestic waste (human waste, FW, and a mix of human and FW) and farm animal waste alone. The examined criteria were the dimension of the digester and volume of the produced biogas.

In the first case, human waste was processed in the digester; the average biogas yield was established at $0{,}024\,\frac{m^3}{kg}$, and the daily human waste production rate was adopted as 0,6 kg. In the second scenario, only FW was applied as the starting material. Basing on the equations used by Maragkaki et al. [134] the volume of domestic waste was established as a function of family members number. Around 40% of the household waste was estimated as biodegradable; 1 kg of FW outputs 0,2 m^3 of biogas [134]. In the third case, human, as well as FW, was used as the feedstock. In the last scenario, domestic animal waste was an input to the biogas digester.

The inputs used in this work can be tailored and adopted as a benchmark for other areas, addressing the aimed PBD convenient for application in diverse regions.

5.2 Rice husk gasification

5.2.1 Electricity generated from rice husk gasification

Regarding the generation of electricity from rice husk in Indonesia, at present, there are two techniques employed for this process: gasification and direct combustion. The chosen technology should:

- present the highest available and possible conversion rate,
- have a desirable thermal efficiency,
- produce limited number of residues.

For electricity generation from rice husk, two mainly used technologies are gasification and direct combustion. Due to more harmful effect of direct combustion on the environment (atmosphere, soil, and water pollution) and the fact that combustion technology is not interesting under 5 MWe to need water treatment, (specific knowledge with steam turbine and relative constant production), gasification was adopted as the preferred technology for small-scale mill electricity access through rice husk valorisation. The gasifier is more modular, flexible, and useful for the small size of the plant (under 5 MWe). Therefore, no MCA was handled for this biofuel.

In this part of the study, it was assessed how rice mill capacity determines its energy demand. Inclining constituents taken under consideration were also processing activities, time of operation, and such factors. For this investigation, the subsequent assumptions were formed:

1. The rice mill's capacity was determined that sufficient husk quantities can be sourced by the mill to satisfy the internal demand for electricity. Moreover, the cost of feedstock was assumed to be zero due to its abundance as a biowaste in the rice mill.
2. Mills with smaller capacities located in a village or rural, small-town location are frequently constructed by local workers and, consequently, consume higher amounts of energy. Therefore, it is estimated that to process one metric ton of raw rice, 43 kWh are utilized [135].
3. Rice mills in Indonesia can be classified based on milling capacity into two widespread groups: small size, processing less than one metric ton per hour, and larger mills. Former commonly run one shift from 6 to 7 hours during around 300 days in a year (i.e., 1800-2100 hours of annual operation) whereas the latter operate on two shifts (from 3600 to 4200 operation hours per year). In this report, it was assumed that a single shift performance for 1400 hours annually.
4. Rice husk accessibility is determined, recognizing that husk represents a 20% mass of processed paddy.
5. The rice husk heating value (HV) is commonly estimated in literature [113] at 15 MJ/kg. For the purpose of this study, HV was assumed at 12,6 MJ/kg.
6. Based on market analysis and review of gasifier producers' offers, the technology conversion efficiency was estimated at 20%.
7. There were no transportation costs assumed in this study since rice husk is a waste product from paddy processing and expenses of its delivery to the facility were appropriated to rice production.

8. Rice husk gasification liquid waste products are tar and wastewater, (produced during cooling down and refining syngas). Calculations did not include the costs of wastewater purification and tar degradation. Solid wastes are principally rice husk ash (RHA), also named biochar. The process of gasification generates an extensive amount of ashes, roughly 20% of feedstock weight [119]. Overall, RHA presents a value and is not toxic for people [123]; however, it has to be disposed of as a bulky material. The disposal of RHA was not considered in economic calculations.

5.2.2 Economic analysis

The below part introduces the practices adopted in the economic analysis. NPV, IRR, Break-Even Time, Payback Time, and LCOE are defined. Moreover, scenario development is considered.

The following calculations presented an optimistic scenario, where assumed values were the most suitable for the model. As mentioned in the assumptions in section 3.2.1, not all aspects were taken into account in the calculations. The work assumes that at the pre-feasibility study stage calculations results may differ from the actual conditions.

〉 Net Present Value

NPV is included in the group of discount methods of investment project evaluation. Its use gives precise and reliable results, which is why it is very often used in practice. NPV is the sum of the discounted cash flows from the investment, reduced by the value of the initial outlay. In simple words, this means that the construction of this method assumes a comparison of the expenses that must be incurred to implement the investment with all the flows that this project will generate in the future [136].

NPV is calculated as follows:

$$NPV = \sum_{i=1}^{n} \frac{CF_i}{(1+r)^n}$$

Where: CF_i – cash flows [US$]
r - required rate of return [%]
n - number of periods [years]

Equation 2 Net Present Value [136]

r in Equation 3 it is the rate of return (concerning the profitability of the project) required by the investor. Thus, it reflects the expectations of people implementing the investment. In this thesis it is assumed at 8% and number of periods 20 years – based on previous EIFER projects.

The result of the analysis is straightforward to interpret. First of all, attention should be paid to whether the received NPV has a positive or negative sign. When the result is greater than or equal to zero ($NPV \geq 0$), the investment should be realized because it meets the investor's expectations.

Otherwise, the project should not be implemented [136].

- Internal Rate of Return

IRR is a measure used in capital budgeting to estimate the profitability of potential investments. The IRR is the discount rate that makes the NPV of all cash flows from a given project to zero. IRR calculations follow the same formula as NPV.

Generally speaking, the higher the IRR of a project, the more desirable it is to deliver it. The IRR is uniform for investments of different types. As such, the IRR can be used to rank many potential projects on a relatively equal basis. Assuming the investment costs are comparable across projects, the project with the highest IRR would probably be considered the best and undertaken first.

$$IRR \Rightarrow \sum_{i=1}^{n} \frac{CF_i}{(1+r)^n} = 0$$

Equation 3 Internal Rate of Return [136]

- Break-even point and payback time

The break-even point is the cut-off point at which the investigated project is neither profitable nor loss-making. At this point, the revenues are equal to the total costs incurred by the enterprise. The financial result is zero. The break-even point is useful in the day-to-day management of the enterprise. It is also used to evaluate investment projects.

The break-even point can be calculated as the ratio of the company's fixed costs to the coverage margin rate. Break-even analysis determines the safety margins (absolute and relative), showing how much, it is possible to reduce sales (by value and percentage) in order not to incur losses.

Payback period (PP) - is the time necessary for the outlays incurred for implementing a specific investment project to be fully covered by the net benefits generated by this project. In a word, this method determines the period (years), after which the investment will pay for itself.

$$PP = \frac{1}{IRR} = \frac{Investment}{Annual\ Cash\ Flows}$$

Equation 4 Payback period [136]

- LCOE

LCOE is the economic estimate of the average total cost of construction and operation of an electricity-generating asset over its lifetime divided by the total energy production of the asset over that lifetime. LCOE can also be taken as the average reserve price at which electricity must be sold to break-even throughout the project life cycle.

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_n + M_n + F_n}{(1+r)^n}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^n}}$$

Where: I_n - investment costs in year n
M_n – operation and maintenance costs in year n
F_n – fuel expenditures in year n
E_n – electricity generation in year n

Equation 5 Levelized Cost of Energy [148]

5.2.3 Social benefits

The approach adopted to identify the social benefits of analysed systems is literature review. Various references for available advantages of bio-waste valorisation were investigated. The leading feasible social benefits discovered were:

- The utilisation of renewable energy,
- Offsetting carbon emissions,
- Reduction of waste,
- Creation of employment for local communities,

The outcomes collected from this chapter were assessed in line with these viewpoints, considering conditions of Indonesian rice plants.

Chapter 4

Analysis of Results

This chapter provides the analysis of research's' results. The results appear in the manner corresponding to the methodology described in Chapter 3. Every section combines its specific findings and review.

4.1 Investigation on biogas digesters

This part of the comparative analysis concerns biogas digesters technologies was relying on the MCA method introduced in Chapter 3 and is divided into the respective two sections.

For French Guiana AD project fixed dome digester, prefabricated digester, and floating drum digester were examined. The guidelines for the examination were chosen subsequent to a literature review related to the expected common properties of biogas digesters for obtaining reliable operation. The chosen digester is required to be:

- operating at optimum temperature 26 Celsius degrees, basing on the average range of temperature in French Guiana [149],
- lightweight, easy to transport and self-assemble, since the only means of transport is a small plane or a helicopter,
- able to contain the volume of waste generated by a typical-size family in rural French Guiana.

In the first part of the MCA analysis, biogas digesters were investigated with regards to four criteria: durability, technical expertise and skills, size, and CAPEX.

The factors weighed in individual criterion, and its importance was outlined in the coming parts.
The MCA findings and parameters' summary were depicted in the performance matrix.

4.1.1 Results of the MCA

〉 Durability

The durability denotes the timeline for utilising the technology prior to its replacement by a new device. This criterion is essential considering it is vital to assure the constant access to cooking fuel, and hence it is favoured to hold high durability to withdraw prolonged interruptions in meals preparation. As specified previously, the typical durability for small-scale biodigesters is fifteen years; therefore, it is assumed that the equipment chosen is operational at a minimum mentioned period.

Table 6 Digesters' necessary maintenance

Type of Digester	Properties
Fixed dome	The digester requires to undergo maintenance and cleaning at least every five years. This process includes removal of settled deposits and fixes potential fractures and cracks in the structure of the digester [137].
Prefabricated	Digester does not need cleaning, due to the production of minimal (1 cm/year) sludge layer [58].
Floating drum	Maintenance as fixed dome + the drum needs to be painted every year to prevent the development of corrosion [137].

Moreover, the durability of these digesters is similar to their preservation and maintenance. Routine cleaning and servicing are required to have an excellent operation for biogas production. This includes cleaning the digester to ensure proper flow of the digestate and to avoid clogging. The summary of the maintenance required for the respective technology is presented in Table 7.

In the light of optimally and regularly performed digesters' maintenance, the durability outlined in Table 8 can be obtained. The values presented are taken for digester operating in areas with high humidity and low yearly temperature amplitude.

The linear function, described in Chapter 3.1 by Equation 1, was applied to modify these values to scores from 0 to 100 interval. In this function, the minimum value corresponds to 0 and the maximum to 100 [133]. Therefore, 15 represents 0 and 30 denotes 100. Based on these two points, a linear graph is created, where the score is represented on the vertical axis and the option's value - on horizontal. As a result, the score for the remaining value can be interpolated. The scores derived were collected in Table 10.

Table 7 Durability of digesters [58, 137]

Type of digester	**Lifespan [years]**
Fixed dome	20
Prefabricated	30
Floating drum	15

〉 Technical expertise and skills

The criterion in this factor relates to the minimal necessary knowledge needed for assembly and O&M of the digesters, which influences the performance of the biogas production directly. The overview of these features for each digester is described in Table 9.

The scoring of technical expertise and skills was completed by direct rating with the following reasoning. If the digester does not need any technical expertise both during installation and operation, the assigned rating was 100. If minimal knowledge is required, the score was 50. Furthermore, if the experience and good system understanding are needed, the score was 0. Outcomes of the scoring were placed directly in Table 10.

Table 8 Technical knowledge and skills for digesters

Type of Digester	**Properties**
Fixed dome	This digester requires excellent technical expertise and background for building and maintenance. The digester's performance and volume of produced biogas are affected directly by the condition and quality of the construction. A lousy structure can result in leakage, influencing efficiency [137].

Prefabricated	There is no required knowledge and experience. The digester is defined by high biogas production performance and low labour intensity. The digester can be established under almost any condition of the environment [58].
Floating drum	Technical knowledge and experience are needed for building and operating the digester. Training of the staff is required [137].

〉 Size

The criterion in this factor relates to the size of the digester, which influences the performance of the biogas production directly. The overview of these features for each digester is described in Table 10.

The scoring of biogas digester size was completed once again by direct rating with the following reasoning. If the digester does not need any technical expertise both during installation and operation, the assigned rating was 100. If minimal knowledge is required, the score was 50. Furthermore, if the experience and good system understanding are needed, the score was 0. Outcomes of the scoring were placed directly in Table 10.

Table 9 Size of the digester

Type of Digester	**Properties**
Fixed dome	For the sake of the economic variables, the advised lower limit of fixed-dome digester size is 5 m^3. Interestingly, digester volumes up until 200 m^3 are identified and viable [150].
Prefabricated	Mostly used to treat food waste and human toilet waste. The volume of the domestic biodigesters available on the market is between 1 m^3 to around 4 m^3 [60].
Floating drum	They are principally applied for conversion of the animal and human faeces based on the continuous-feed method. Mostly adopted by modest size farms from 5 m^3 to 15 m^3 of volume or in bigger agro-industries from 20 m^3 to 100 m^3 units [150].

〉 CAPEX

The CAPEX is the cumulative cost to enforce the biogas digester; all pipes, materials, and composites required for biogas production are contained in the CAPEX. Parameters like digesters' dimensions, material, and preparation of the workers are diverse for individual cases. As a result, the digesters are categorised from the least to the most expensive:

1. Floating drum digester,
2. Prefabricated digester,
3. Fixed dome digester.

Once again, the direct rating was applied to score this criterion. The best score was awarded to the digester with the lowest CAPEX and the weakest score to the most expensive technology. The outcomes can be observed in Table 11.

- Performance matrix

The outcomes of the MCA are shown in the performance matrix. In order to finalize the matrix, the weight for every criterion was assigned. The measuring was performed by distributing 100 units among the criteria. Durability and technical knowledge were assigned 30 units out of the 100, whereas size of the unit and CAPEX received 20 units. The linear additive model determined the cumulative scores described in Chapter 3. The final results of the MCA were illustrated in Table 11.

The most significant score from the MCA determines that the technology adjusted the best to the requirements of rural and remote areas of French Guiana is the prefabricated digester.

From here, the figures and design applied were relying on the properties of the technology mentioned above.

Table 10 Outcomes of the MCA

Type of digester	**Durability 0,3**	**Skills 0,3**	**Cost 0,2**	**Size 0,2**	**Score**
Fixed dome	33	0	0	0	**10**
Prefabricated	100	100	50	100	**80**
Floating drum	0	50	100	50	**45**

4.1.2 Establishing size of digester and biogas production

This part introduces the evaluations of biogas volumes which can be produced by handling the bio-waste applying the prefabricated digester. As stated in part 3.2, the evaluations were made to establish the volume of the digester, as well as the size of a family and used feedstock bio-waste to offset LNG utilisation through the valorisation of organic waste.

The conclusions of the digester's capacity were attributed to two criteria: size and the biogas production rate. The former was essential to define its potential to be applied in the prefabricated version, while the biogas production was significant to discover how beneficial introduction of the digester was to substitute LNG to meet the family's cooking fuel demand.

The significant fraction of bio-waste available for the AD process can be human waste but considering that families in rural areas have their food leftovers from meal preparations, and those leftovers hold a rate of biogas production, those scraps can be combined with the overall waste to analyse the advancement in the production of biogas. It was assumed that each family member produces 400 grams of faecal waste per day and the HRT is 60 days.

The digesters' volume relying on household waste and the different size of family is displayed in Figure 4.1; the one that utilises a mix of human and FW holds the most significant size, and it remains remarkably close to the one handling human waste alone. As the number of family members rises, the difference in respective digester size becomes more notable. Figure 4.1 further reveals that the digesters' volume processing solely FW was the lowest.

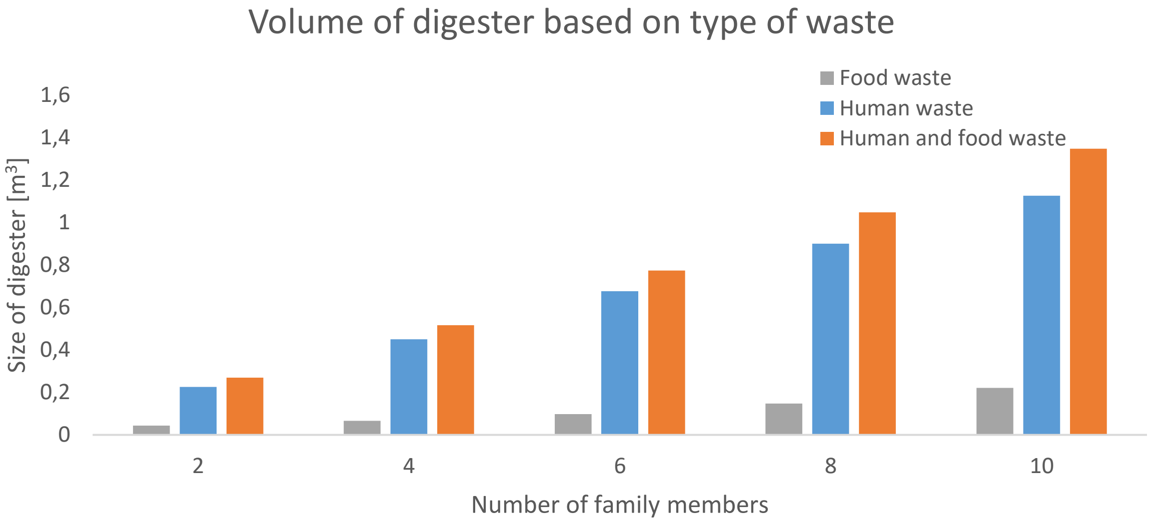

Fig. 4. 1 Size of digester as per bio-waste type based on calculations

The findings of biogas gas production from digesters are provided in Figure 4.2, which shows that adopting the human and FW blend as a feedstock supplied 120% more gas demand for cooking concerning a family of five. In parallel, the employment of only human waste or only FW as feedstock contributed to 67% and 45%, respectively. As for the individual digester, FW alone could supply the entire LPG cooking gas demand, whereas a digester applying only human waste fails to cover it. With the increase of the family size, the number of food residues increases as well; therefore, digester loses its efficiency and capability to meet the LPG cooking demand. Figure 4.2 presents that digester based only on human waste meets only 38% of the five-person-family’s requirement for LPG. Ultimately, the converging lines representing LPG and the food–human waste will meet, indicating that an expansion of the family members will limit the digester from satisfying the family’s need for LPG.

Table 11 Outcomes overview for five-person family size

Type of digester	**Size of digester [m^3]**	**LPG replacement [%]**
Human residues	0,5	67
FW	0,09	45
Food-human waste	0,55	120
Animal dung	2,11	>400

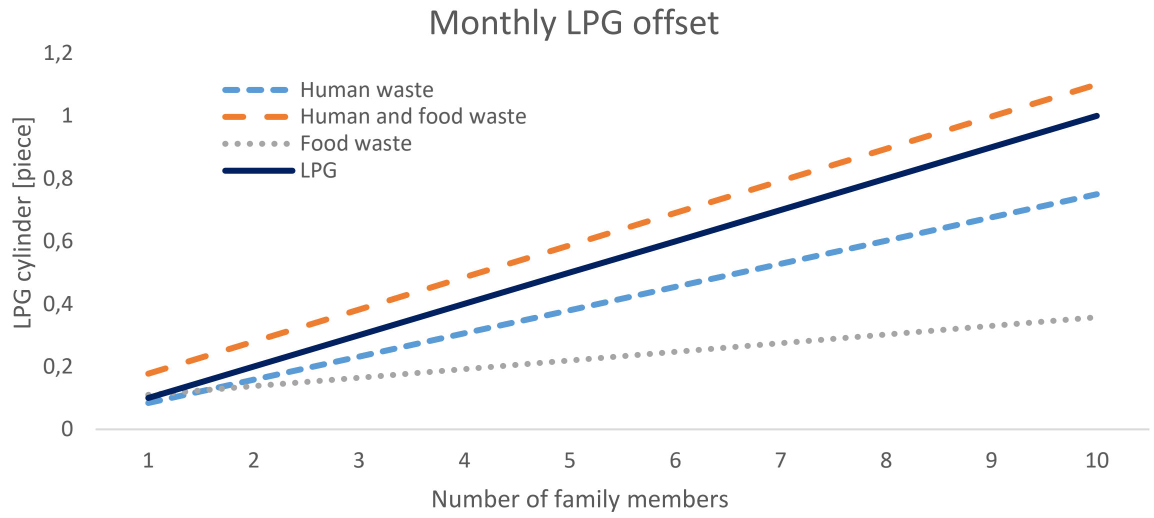

Fig. 4. 2 Compensation of LPG cylinders per type of bio-waste

The last digester feedstock design used animal manure, which was considered fixed despite the family size. The adopted type, number of animals, and daily produced waste were as follow: one cow (10 kg of waste), two sheep (2 kg), and seven chickens (0,08-0,01 kg) [138]. Table 6 presents the estimated biogas production as per the feedstock origin. Figure 4.3 shows the volume of produced biogas from domestic animals' waste associated with food-human waste and LPG demand as a reference. In comparison to a family of five, digester fed with only animal manure can meet the cooking gas demand four times. The surplus of fuel can be applied for lighting, whereas the food and human waste digester satisfied 120% of fuel demand.

The overview of the findings of the three examples of the biodigester size and capacity of gas production was given in Table 12. The family size, on average, was assessed to constitute five, based on the Insee - National Institute of Statistics and Economic Studies of France [139]. The gas vessel was compared to the typical LPG cylinder used for cooking purposes that, as stated by *Société Anonyme de la Raffinerie des Antilles* - French company operating in West Indies-Guiana region, holds 12,5 kg of LPG.

Table 12 indicates that human waste satisfies 67% of the requirement for cooking gas per month and can be improved by FW to meet 120% of needed gas. On the contrary, animal waste is able to satisfy the cooking gas need more than four times; however, the obstacle was, to a large extend, enlarged digester size.

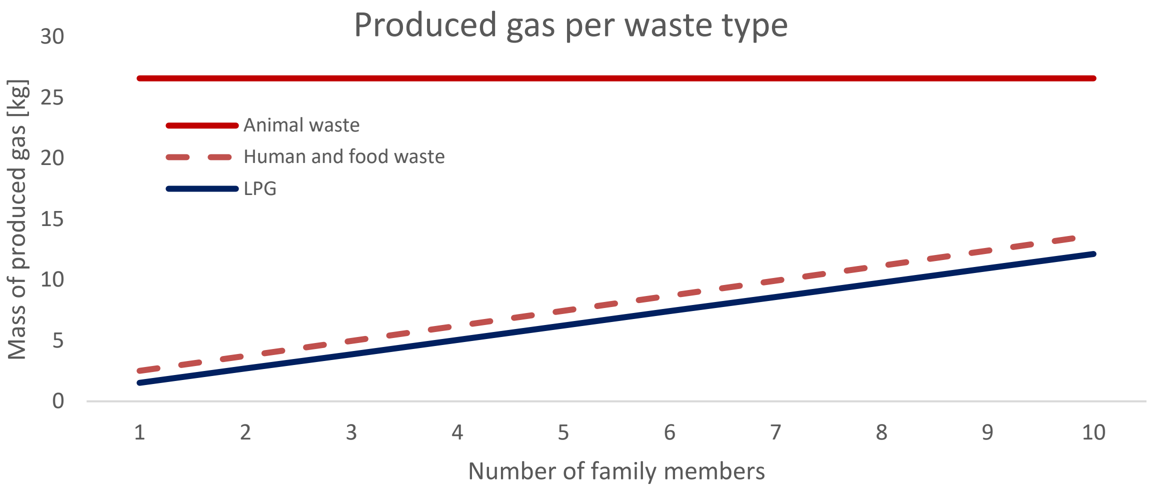

Fig. 4. 3 Mass of produced gas as per waste origin

4.2 Rice husk valorisation analysis

4.2.1 Electricity generation

〉 Supply of feedstock

This model was based on a theoretical solution, describing a small-scale rice mill concerning what could be established, including rice husk as fuel. It was assumed that rice mill was provided with rice husk from its' production, and it, for at least, provided electricity for itself. Considering the intended capacity for stable operating conditions (6 h/day) was 1 500 tons per month, needing 18 000 tons per year of raw material. Suppose the estimated projected operating time increased to 12 hours per day, the amount of processed raw material increases to 36 000 tons/year.

Smaller mills with lower milling capacity located in the neighbourhood could turn into potential partners as feedstock suppliers. Nevertheless, as rice husk is considered a potential biofuel, the cumulative CO_2 emission is equal to zero as a result of CO_2 consumption by rice paddy. As all the CO_2 in rice production is recycled, the share of emissions would be added through transport, which contributes to over 60% emissions related to paddy processing [119].

No comprehensive investigation of demand fluctuations during the year or day was done. Alternatively, a comparable amount of a total load of operating hours was applied for calculations. As reported by a feasibility study conducted in Cambodia and practice from already available projects, it was plausible to presume 1800 h per year of the full load performance for rice mill. Considering that rice husk is released through the milling process, rice husk as a fuel for power generation is accessible through an identical period as the electricity demand exists, which means that plant utilising rice husk has the same number of operating hours as those mills.

〉 Electricity

It was assumed that the total generated electricity could be used or sold if produced. The mill lacking a grid connection is expected to work to suit the power load which it is connected to firmly. Any indications of trouble to manage load fluctuations or surplus/ shortage of power as a consequence of it was not reviewed. As long as it is feasible to retail electricity at any given moment, the calculated LCOE matches the electricity sale cost where the project attains economic break-even. This implies that the LCOE can be compared to current and future electricity tariffs.

Due to PLN's existing monopoly on state grid distribution network, the estimated electricity price is reliant on the electricity being traded straight to the user or to the state power grid. The electricity price was fixed for operation during the day to the industrial purchase rate for the grid voltage intensity that majority of rice mills are coupled with [140].

Relying on the raises explained above and present electricity prices in Indonesia, this charge was assessed to 25 ¢US$/kWh. Rice mill was intended to trade surplus of electricity to the state grid and therefore depends also on the Indonesian feed-in tariff. Basing on a Policy Brief [141] this value was assessed as 10,71¢US$/kWh. All prices excluded taxes.

4.2.2 Technical-economic evaluation

This part gives the analysis and results of the technical-economic evaluation. As discussed in the preceding part, the economic evaluation relied on information about the chosen technology for rice husk valorisation. The findings of the investment returns were described in this section.

The figures and values employed in the economic evaluation were obtained from various literature references.

〉 Capital expenses (CAPEX)

The CAPEXs describe the cumulative expense invested in the rice husk gasification system. The entire CAPEX comprises the own - acquired capital and loans. Moreover, the lifespan of the technology was presumed to be 20 years which signifies the typical lifetime for rice husk gasifier.

Land expenses were not reflected in this investigation as it was concluded that investment is carried out on existing premises of a rice mill. The expenses for the technology contain the gasifier (fluidized-bed reactor), IC-engine, SI gas engine, cyclones and scrubbers, conveyor belt, and electrostatic precipitator. Those expenses were associated only with rice mill; the distribution for outside connections was not included.

The values adopted in this part were adapted from various research references. The total CAPEX combines all expenses of rice husk gasification unit for the standard plant value of gross 1,4 MW_e capacity and amounts to 1,6-1,8 kUS$/$kW_e$.

Cash flow estimations included the technology depreciation by distributing the CAPEX to identical values over its lifespan.

- Operational expenses (OPEX)

Operational cost involves total expense required for the handling of the bio-waste, containing expenses for the labour and workforce (administrative and operational). The expenses for energy utilised during the operation were not included as it was estimated total energy demand was satisfied internally. The OPEX was calculated and assessed to be 4,5% of the CAPEX and confirmed based on values from previous EIFER projects. Operational cost covers the expenses for repairs, servicing, and comprehensive maintenance of the devices.

The cost of insurance of the bio-waste plant was estimated in this study at a commonly accepted value of 0,5% of CAPEX.

The labour costs were acknowledged in regard to the minimum wage in Indonesia 257 US$ per month for manual workers and 290 US$ for administration. The transport expenses were not determined in this study, and all internal feedstock movement was included in the auxiliary consumption.

- Revenue

The revenue of the bio-waste plant was earned from the feed-in tariff. The assumption was that the volume of rice husk to be gasified was accessible without disruptions and that power generation was consistent through the complete lifespan of the project.

The estimation of the electricity revenue was relying on the surplus electricity open to be contracted and the feed-in tariff. The electricity available was 1 494 000 kWh per year (based on estimated available volume of rice husk) and the feed-in tariff, introduced by the Indonesian Ministry of Energy and Mineral Resources [141], was assessed as 10,71 ¢US$/kWh. Aggregation of the data applied to estimate revenue can be viewed in Table 13.

Table 12 Information applied to calculate revenue

Element	**Value**	**Unit**
Industry electricity	25	¢US$/kWh
Feed-in tariff	10,71	¢US$/kWh
Annual net	1,494	GWh

4.2.3 Economic analysis

This section shows the outcomes of economic analysis, based on calculations and estimations described in Chapter 3.3 and 4.3. Two models were taken into consideration based on daily operation hours: Model A with 6 h/day and Model B with 12 h/day.

〉 CAPEX and OPEX

The capital expenditure for both Model A and Model B were addressed to be identical, whereas the operational expenditure was higher for Model B due to additional 6-hour shift, and consequently, higher salary. Additionally, the cost of the feedstock was assumed to be zero because it is a residue from rice milling process. The overall costs comparison can be viewed in Table 14.

Table 13 Comparison of cost Models

	Model A – 6h	**Model B – 12h**
CAPEX	Cost [k US$]	
Gasifier and gas engines	1 048	1 048
Construction	104,7	104,7
Engineering	105	105
Other costs	45	45
	1 458	1 458
OPEX		
Spare Parts and labour	51,03	58,32
Insurance	7,29	7,29
Other maintenance	7,29	7,29
	65,61	72,9

〉 Revenues and savings

As previously mentioned, the revenues originate from the feed-in tariff. The outcomes of calculations for both Models are presented in Table 15. Savings from internal electricity generation were also included.

Table 14 Comparison of revenues and savings

	Model A	**Model B**
Rice mill self-consumption [GWh]	1,026	2,052
Electricity savings [k US$]	256,5	513
Net power generation [GWh]	1,494	2,988
Revenues [k US$]	160	320

〉 Return of investment

Based on data presented in previous parts, calculation of the Economic Performance Metrics was performed. Outcomes of each calculation for both Models are presented in Table 16. What can be observed is that the NPV values are alike positive, which designates that the Models are economically feasible. Model B was more attractive, as the NPV and IRR were higher than for Model A. In both cases, values were positive; therefore, rice mill can recover the cost of investment and receive benefits from implementing rice husk gasification. Moreover, the IRR scores from both Models were more significant than the supposed discount factor of 8% backing up the outcomes of the NPV approach. In terms of the break-even and payback time, Methods presented the same results for prior - 2 years and diverged in case of latter. About seven years are required for 100% return of CAPEX in Method A, whereas the implementation of additional 6-hours shift decreases this time almost in half.

Table 15 Comparison of Economic Performance Metrics

Economic Performance Metric	Model A	Model B
NPV [k US$]	2 034	6133
IRR [%]	21,23	41,31
Break-even time [years	7	4
Payback time [years]	2	2

〉 LCOE

The LCOE induced 9,34 ¢US$/kWh for Model B. Reflecting on this method solely, Model B is the preferred option due to the lower value of LCOE. However, this approach assesses the expenses of generating electricity exclusively. Therefore, LCOE can be applied to compare energy expenses from diverse technologies and not to compromise decision-making like it is with the NPV and IRR approaches which assess the total project cost and revenue also covering the energy price.

Analysing the outcomes of the LCOE for Method A and Method B with the energy cost in Indonesia, it was observed that the variation between these prices is characteristic. The LCOE estimations calculated were lower than the present electricity price, 25 ¢US$/kWh, in both cases. This variation was principal to the fact that electricity generated onsite does not contain any transmission fees, which makes it more competitive in comparison to electricity from the grid.

Table 16 Comparison of electricity prices

Reference	LCOE / electricity price [¢US$/kWh]
Model A	18,68
Model B	9,34
Indonesia	25

4.2.4 Social Benefits

Various benefits can be acquired through the implementation of rice husk gasification and bio-waste treatment in general. The advantages described in this part are a review of the profits determined in the literature respecting bio-waste valorisation executed in diverse regions and the potential benefits for Indonesia.

〉 Source of renewable energy

Climate change consistently confirms its presence and shows the consequences of its attendance. Hurricanes, flooding, storms, and ecological catastrophes are showing seasonally throughout these decades. Indonesia, positioned at 39th place of the Climate Change Performance Index [142], continues to perform low when it comes to emissions reduction. The implementation of bio-waste valorisation technologies can support and promote diverse regions of Indonesia to become contributors to climate change mitigation. Indonesia is a country with an abundance of coal, which causes it to be greatly dependent on it. This fossil fuel is profoundly pollutant, and consequently, different energy sources and supplies need to be examined. WtE technologies could match these requirements and pose feasible alternatives to overcome coal dependency and reduce emissions in Indonesia.

〉 Reduction of waste

The application of the rice husk gasification could decrease the volume of waste being dumped or illegally incinerated. Yearly, up to seven thousand tons of bio-waste from one, average-size mill could be utilized. This perspective can also be combined with the mitigation of GHG emissions, considering that avoiding open-air incineration reduces them. Additionally, biochar produced from the gasification of rice husk is also a good fertilizer.

- Employment creation

The introduction of this project can create employment opportunities for local inhabitants. It was determined that a possibility of eight new job openings could be created for the gasification plant: six positions for the system operators and two managerial positions.

Furthermore, this project's realisation in one of the Indonesian rice mills can be the driving force for introducing bio-waste valorisation technologies in other mills in the region or country. Consequently, this could lead to the generation of more substantial job possibilities for Indonesians in rural areas. Bio-waste technologies require operators, managers, and administrators to operate the systems and qualified technicians to construct and install it, which could contribute to short-term benefits and long-term returns for the citizens.

Chapter 5

Conclusions

This chapter finalises Master Thesis, summarising conclusions, and pointing out aspects to be developed in future work for each of the three pre-feasibility studies.

5.1 French Guiana

Size and biogas yield are the benchmarks for regulating the form of a prefabricated digester. To begin with, investing in a prefabricated digester can tackle the waste management challenge of rural communities and decrease family’s monthly LPG expenses. Furthermore, it was remarked that a digester fed with animal manure outputs the most significant biogas yield and meets more than four times the monthly cooking gas demand for a family of five. Interesting units applicable for such an application were listed and included in the Annex A of this work..

Moreover, organic fertilizer could be obtained from the slurry produced during the AD process. Both human and FW digesters satisfy the prefabricated size specification with digester measurements for 0,5 m^3 and 0,1 m^3, respectively. Alike, they have reduced biogas efficiency, which meets 67% and 45%, respectively, a demand for cooking. Subsequently, the best digester dimensions were related to a feedstock of food-human waste mixture. This digester fulfilled the prefabricated size specifications, with a volume of 0,55 m3, and satisfied 120% of demand for cooking for a five-person family.

Various and diverse topographical areas, the influence of climate, and varied family members number could demand few alterations in the design; nevertheless, it could also produce the needed amount of biogas to match the requirement of a rural household elsewhere in the world.

Basing on market data and literature review, it was concluded, considering the overall lifetime of biodigester is around 20 years, that the investment cost for the prefabricated digester opposed with the fixed dome digester, is more economical. Besides, the initial capital expenditure of the former was approximately 30% that of the latter. The analysis of the LCA revealed that plastic prefabricated digester prompted the most significant environmental impact as a consequence of the comparatively short-term lifetime of plastic elements. The most significant environmental impact of the fixed-dome digester was related to concrete and bricks. Ultimately, the primary convenience of the prefabricated digester was its easiness of application and handling, as well as much lower initial investment cost as opposed to the fixed-dome model, which seemed to occur more environmentally sustainable [58].

According to available research analysis, it was determined that biogas generation, compression, and storage are a financially viable undertaking for the rural families where significant volumes of food-human waste are obtainable. It was established that biogas could be compressed and put in the LPG cylinder, for storage or transport. To adapt biogas for the cooking application, the gas should be compressed to around four bars after refinement. Nevertheless, in general, it is not necessary, and utilisation of uncompressed biogas is safer. The best way is to use it directly or with a small bag storage for one or two days.

Moreover, the viability study for families is defined by cost-saving, timesaving, and revenue from bio-fertiliser. A significant part of biogas household users reports abovementioned savings as a notable compensation of the technology. Advantages of bio-fertiliser can frequently be more relevant in economic terms by creating revenue or decreasing the expense of farm means of production. Transformation of bio-waste into bio-fertiliser could minimise its impact on the environment, advance nutrition ranks of the soil, moderate demands for artificial chemical fertiliser and become a straightforward bonus on food production.

5.2 Indonesia

There is an abundance of rice husk in Indonesia from which only a fraction is utilised. If total rice husks formed through rice mills operation in the country was used for electricity generation, it could satisfy nearly 2,04% of the existing electricity demand. This research estimated that every year roughly 5,04 GWh of electrical power could be generated and save 830 000 US$ by utilising 7,2 thousand tons of rice husks toward more affordable electricity.

The owner of the rice mill could employ their bio-waste production to provide electricity to the grid, supported by the feed-in tariff system. Out of various rice residues, solely bio-waste in the form of rice husk is considered economically viable as a bio-waste solution for electricity generation from the agricultural rice sector [119]. Since 2015, the feed-in tariff for small and medium bio-waste projects (up to 10 MW) contracting their electrical power to PLN is 10,71 ¢US$/kWh. The highest technical and financial potential emerges on Java and Bali, where the majority of rice plants are located.

Alongside revenue from electrical power generation, trading rice husk ash could become a source of further income. Ash is a relevant asset which can be sold as a filler for the ready-mix concrete manufacturers, as non-conductor in the steel production, or as filter material in various industries. The sell-outs of the ash might actively enhance project profitability. Rice husk ash reaches a market value of about 86 US$/ton [145].

Additional and interesting savings / income source for bio-waste project like this, could be the application of carbon contracts. The tradable carbon credits model is used to calculate avoided CO2 emissions through the generation of electricity using bio-waste alternatively to fossil fuels. Contracts can be manifested in the formation of the potential revenue that might be made by applying renewable technology. Currently, Indonesia does not practice this mechanism, but first concepts and drafts for the regulation have been started at the end of 2019 [146].

The milling capacity of the rice industry in Indonesia is widely different. It varies between 4 and 100 tons of paddy per day in smaller, family-owned mills, and up to over 1 000 tons in industrial mills [145]. The economies of scale are another significant determinant for the saving possibilities. In general, smaller rice mills run just several hours per day, hence humbler savings. Introduction of additional shift resulted in overall higher profitability of the project, which was confirmed by greater values of Economic Performance Metrics, i.e. NVP, IRR, and payback time. A feasibility investigation could be initiated for a larger scale project, e.g., 5-10 MW. The electric power could be traded directly from the rice mill to the nearby area and surplus of electricity could be sold to the national grid through feed-in contract. The compliance to pay a premium for a reliable and stable supply of power could likely bring a source of investment or PPA, particularly from commercial and industrial users.

The large-scale power generation can turn out to be economically feasible and further reduce the environmental impact of singular rice mill. Additionally, a larger scale could potentially lessen the burden of the rice mill to manage and administer such a system. To be up to date with a fast-changing milling industry, it was recommended to develop a combined technical support program which could provide information and knowledge on possible investments and profitability of the investment. Furthermore, to provide commercial support, rice mills likewise require high-skilled workers and operators to run advanced machinery and be proficient with appliances driven by electricity. Schooling and training organisations could give such training to current workers or combine needed experience in their program.

Gasifiers are not simple in operation in small industries like village rice mills. Experience from other countries, like India, indicates that small steam engines could be used for similar power demands. The steam engines have a comparatively affordable price, and no supplementary diesel is needed to manage them. In comparison to gasifiers, steam engines can utilise any bio-waste type and bear higher moisture content. Additionally, they do not produce tar or wastewater contamination. The viability and efficiency of this technology need to be assessed and examined in a pilot project.

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Annex

Annex A. Biogas digesters available on the market

Annex B. Business Model

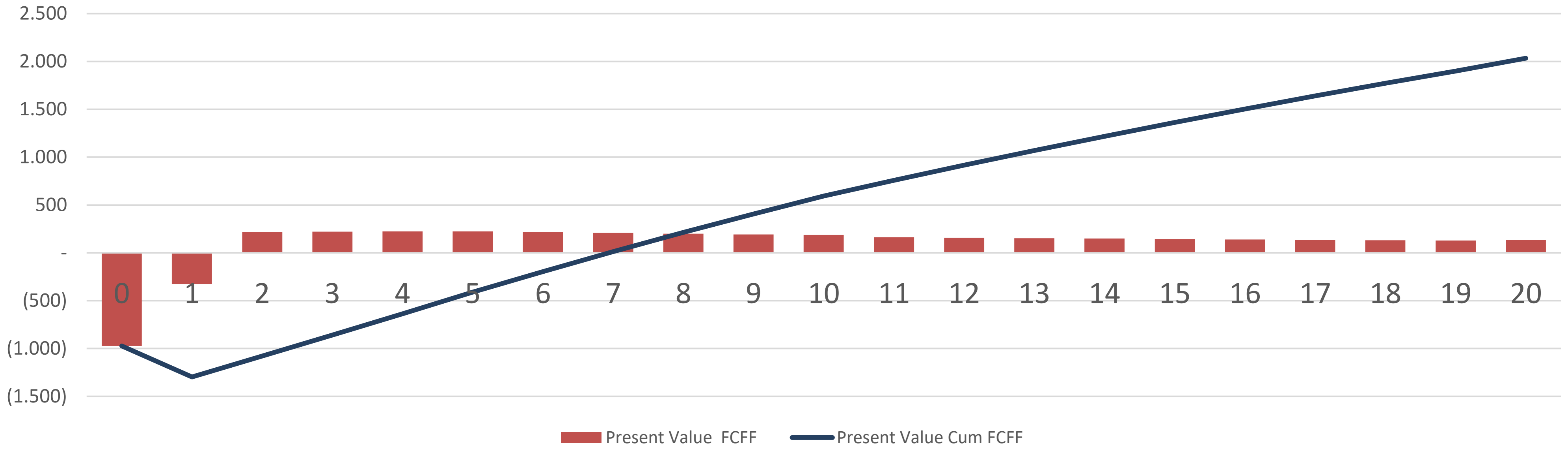
Annex C. Biogas-based electricity generation from Municipal Solid Waste

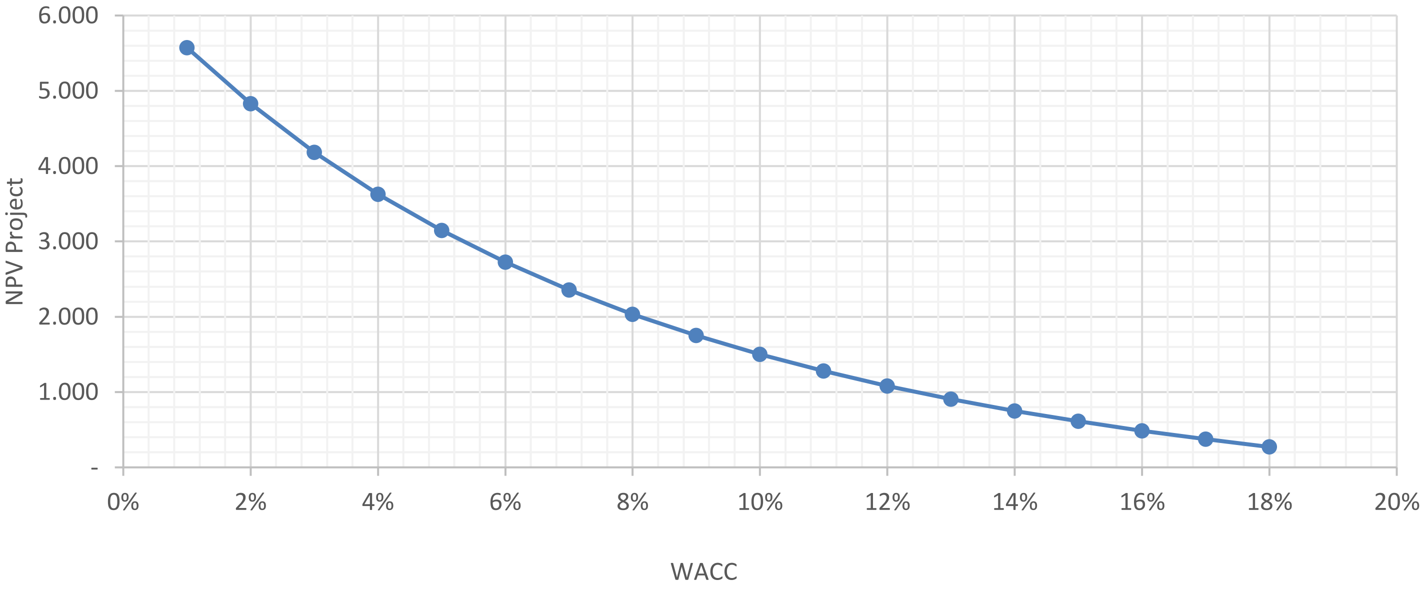
Annex A - Biogas digesters available on the market

Name	Capacity [kg/day]	Size [m^3]	Biogas production [m3/day]	Feedstock	Uses	Price	Country	Notes
Earthlee MicroDigester (RapidDigester)	19	n/a	2,9	cattle manure, FW	hot water, cooking	n/a	Austarlia	This equates to 2,247 hours per year (using a 1.5kW biogas burner ring with a flow rate of 0.471m3/hr) –up to 6 hours of cooking time per day.
Ökobit (HoMethan)	max. 200	n/a	~5	manure	cooking, baking, electricity	n/a	Germany	Manually operated stirring system
HomeBiogas	6 l kitchen waste, 20 l animal manure	n/a		kitchen waste, manure	cooking	650$	Israel	Additional connection for bio-toilet possible. French utility ENGIE invested in this company
PUXIN Portable Assembly Biogas System		3,4 m^3	~2	FW, pig, cow, and chicken manure, human waste, vegetables	cooking, lightning	start from 550$	China	
Hestia Home Biogas	~ 6	n/a	0,15 - 1,7	household organic waste	cooking, lighting, and space and water heating, gas refrigerator or chiller	n/a	USA	
FAV BIOGAS	n/a	1 - 1000	n/a	FW, cow dung, night soil biogas plants and multi	n/a	n/a	India	BioCNG generation, the volume of gas required will be

				feedstock-based biogas plants				minimum of 1000 m3/day
MyGug	2,66	n/a	1-2 h of cooking	kitchen waste only	biofertilizer, cooking	n/a	Ireland	http://www.mygug.eu/faqs.php
Home Biogas Kenya	n/a	0,5 1,7 8,3 and 54,38	0,5 2 8 and 50	kitchen waste	biofertilizer, cooking	n/a	Kenya	https://homebiogaskenya.co.ke/domestic-biogas-systems

Annex B.1 – Rice husk gasification - Business plan – Model A

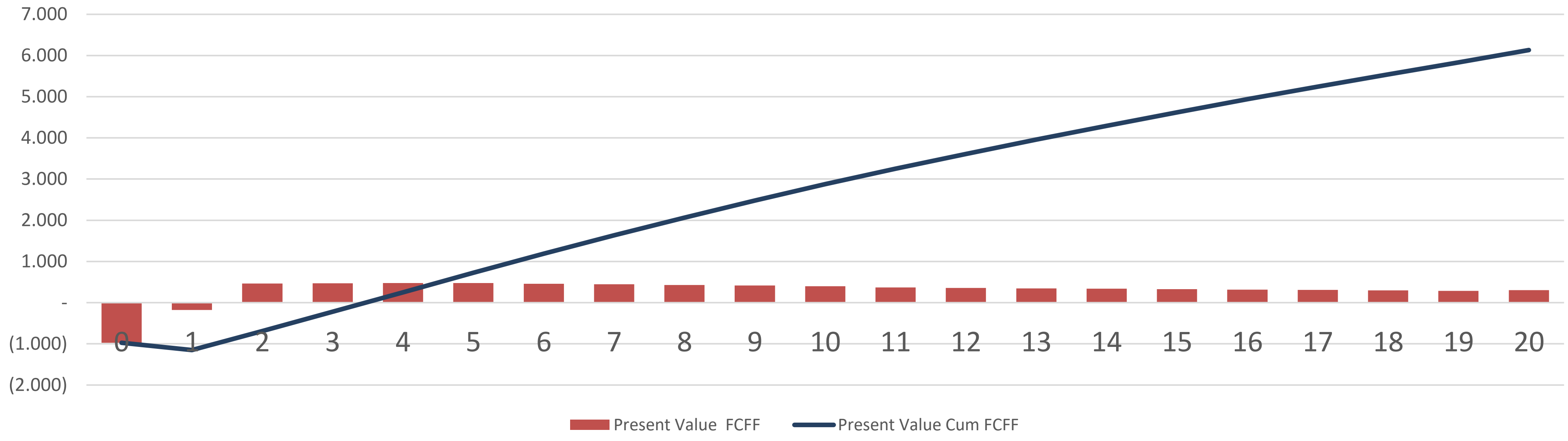


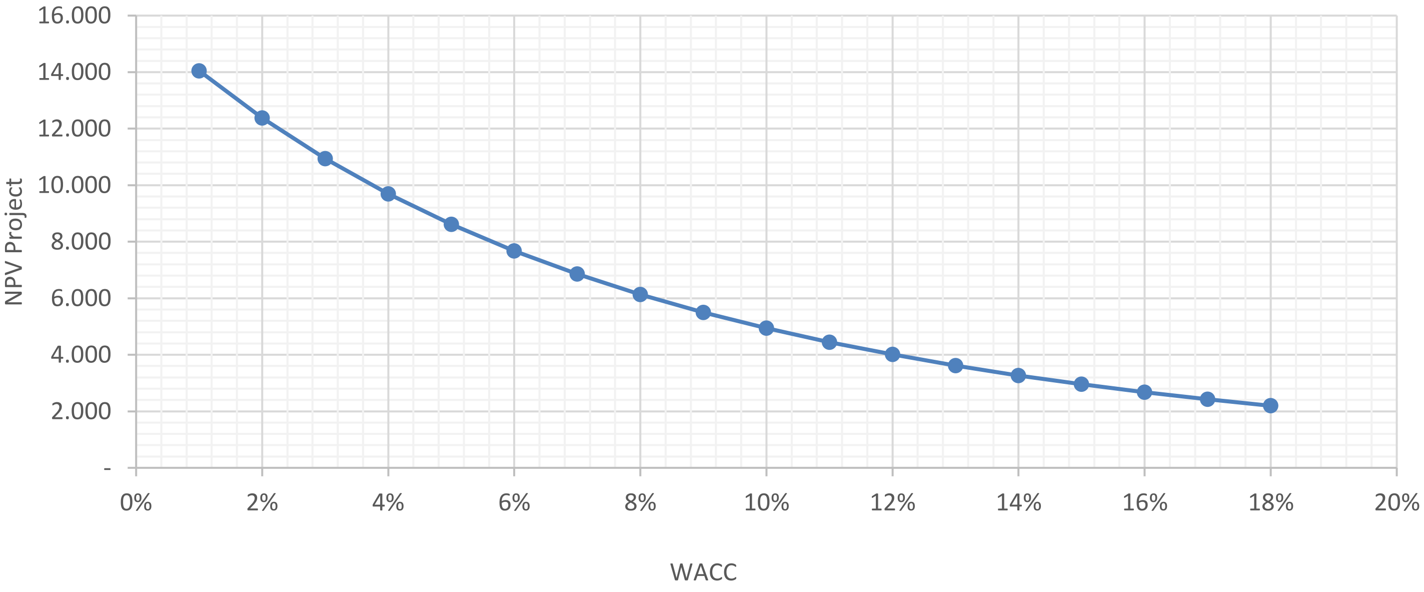


NPV Project	**2.034**
IRR Project	**21,23%**
Excess return	**13,23%**

Break-even Time	**7**
Payback Time	**2**
Cash Investment	**(1.297)**

Annex B.2 – Rice husk gasification - Business plan – Model B





NPV Project	**6.133**
IRR Project	**41,31%**
Excess return	**33,31%**
Break-even Time	**4**
Payback Time	**2**
Cash Investment	**(1.151)**

Annex C - Biogas-based electricity generation from Municipal Solid Waste

Biogas-based electricity generation from Municipal Solid Waste

The socio-economic advancement of nations around the globe is greatly affected by an untarnished environment and cleaner energy supply resources [70, 71]. Worldwide, MSW generation has expanded drastically as a consequence of population growth, economic advancement, progressing urbanization, and shift in consumption models [72]. The output of MSW generation around the globe is believed to approach 2.3 billion tons by the year 2025, and 4.3 billion by 2050 [73]. This development has a significant adverse effect on the climate and the environment. Municipalities around the globe are estimated to cause around 70% of overall GHG emissions, and MSW production notably contributes to those emissions [74]. Waste control is a challenging responsibility for local authorities in emerging economies, which is mostly caused by the expansion in volume and heterogeneity of solid waste, spare financial capacity, deficient core technologies for handling and treatment of waste, and weak implementation of MSW regulations [75].

Solid waste management and opportunities in developing countries on example of Ghana

Proper WM figures deliver comprehensive resources for a thorough, observant, and explanatory assessment of WM choices in all WM plans [76]. These necessary statistics are, unfortunately, deficient in various developing countries [77] whereas in regions they are available, present inconsistency because they originate from several sources which may not be verified and are often based on assumptions not supported by scientific measures [78]. The apparent consequence of this incorrect data is frequently a cause of confusion and uncertainty in the perceptions of stakeholders who may desire to create business or service opportunities in the sector of WM. Ghana remains indifferent to this information deficit issue. Data on MSW formation and structure are accessible in only a few certain cities, in the vast majority collected over a decade ago. National waste data, in general, is insufficient; ground survey on domestic waste composition and production has not been handled comprehensively in the ten country regions; consequently, reliable data that could ensure access of this information to the regional and federal WM officials for decision-making is lacking. Individuals and resource capacity to perform these investigations, which includes the gathering of explanatory information on waste quality and quantity that is transported to processing sites, recycling facilities, or disposal centres, are deficient [79].

MSW and household waste are commonly generated from various sources where diverse human operations are faced. Numerous studies point out that a substantial part of MSW from developing nations originate from households (50–75%), followed by trade or market zones (15–25%) with alternating loads from streets, commerce, and institutional facilities among others [80]. Waste originating from sources mentioned above are significantly heterogeneous [81], and present inconsistent physical characteristics subject to their sources; mainly they are composed of waste of various origin like FW, garden waste, wood, plastic, carton and paper, metal, leather, rubber, inert material, batteries, diverse containers, textiles, building materials, and several others, potentially challenging to categorize (Fig. A.C.1). The diversity of the formed waste represents a significant difficulty in its further operational use as a feed material. Therefore, it is necessary to fractionate the waste prior to their substantial treatment process. Separation and segregation of waste are some of the conventional fractionation methods and primary steps in a combined WM system that offers statistics on the waste formation and the properties of the fractions. Nevertheless, the favourable outcome of any intended waste segregation system relies mainly on the effective cooperation of waste-generating facilities in several districts and in what way they respect the policies of waste sorting and separation. The waste generated from industrial and commercial premises in Ghana is complex to evaluate on a per capita basis, given that not all the sources are known. Evaluation is mostly performed on the bulk of the collected waste. The composition might rely on industry commercial activities, e.g., food markets; other interesting sources to obtain correct data for managing waste could be households, hotels, and restaurant industries [78].

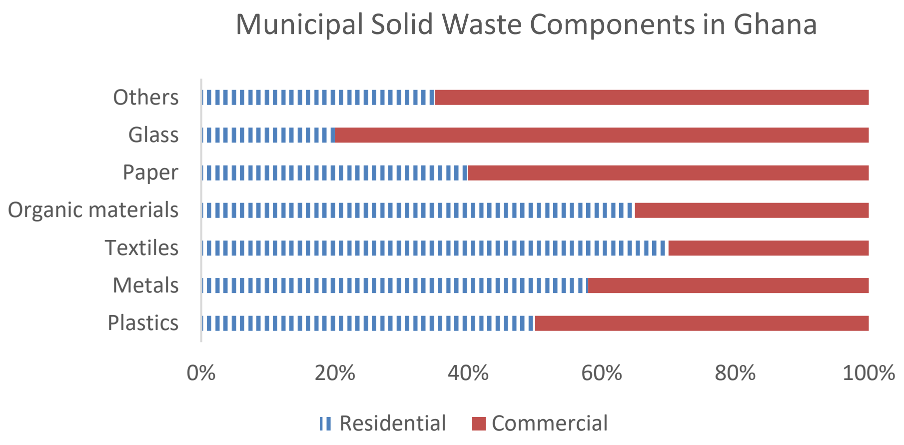


Fig. A.C. 1 - Constituents of MSW created in Ghana [83].

Among other regions, Africa has high potential in biogas generation from waste; however, it has obtained little in evolving the sector. Although the region has made development in small-scale, artisanal, or household biogas digesters [82-84], commercial bio-systems remain immature [85]. Various nationwide and local investigations have been undertaken on the feasibility of biogas implementation in Africa, across technical issues through economic and political analysis. Research conducted in Ghana, the fourth country with the highest installed electricity generation capacity on the continent [86], pointed out that albeit about 100 biogas plants established in the country [87], merely 44 have been operating in good condition. Within those functioning, around 58% are institutional plants. The rest are community and domestic plants with unknown capacities, all private projects, and producing biogas for internal utilization [88].

In Ghana, industrial biogas plants involve a 1500 m^3 palm oil waste digester and an 800 m^3 fruit waste digester from a fruit processing company. Single biogas plant in the country, which is connected to the grid, a 100 kWe facility processing human waste and organic waste from the market, commenced feeding electricity to the national grid in the second half of 2016. Research on biogas potential has been carried out in Ghana, where an abundance of information sources abides for biogas production [89]. The achievable potential of biogas formation from crop and forestry residues, livestock manure, and MSW is assessed at 2700 Mm^3 per year [90]. There is a significant capacity to generate biogas from MSW, in particular for municipalities where 500−850 tons of refuse is formed daily [91]. It was estimated [92] that this technology can be applied to generate 1–1,5 GWh electricity per year from MSW.

The primary MSW management approaches implemented in Ghana involve recycling, composting, using engineered landfills, and waste incineration (Table A.C. 1). Efficient enforcement of these treatment and disposal approaches has not been obtained in this country throughout the years. Sending waste to landfill and incineration are performed without appropriate capture of emitted biogas or flue-gases and valuable outputs from the AD and waste treatment technology [93].

Paper, scrap metals, and plastic waste are the prime recyclables that are formed abundantly in Ghana, thereby growing the market necessity for the recycling industry. On the contrary, the collection of the wastes mentioned above is at present challenging in Ghana as a consequence of inadequacy in more affordable and proper technology for waste sorting; therefore, only a handful of companies are engaged in MSW recycling. Nevertheless, there are existing WM programs launched by Zoomlion Ghana Limited (WM and environmental sanitation businesses) to support promoting the efficacious collection of wastes via providing households with storage containers for all sorts of waste. This move may further be improved by supporting waste sorting at its origin (i.e., residences, offices) through education of the community [94].

Table A.C. 1 - Waste disposal practices in Ghana [94]

Waste disposal methods	**% of MSW**
Dumped (landfill / incineration)	31,4
Collected (landfill / disposal)	51,9
Unauthorized disposal	10,1
Household disposal (burned / buried)	2,9
Recycled	2,1
Composted	1,4

Possibilities for hybrid solar PV integration for decentralized areas

Hybrid systems generally combine two or more diverse sources of power such as photovoltaics (PV) and wind turbines, PV and solar, biogas with wind energy, biogas with hydro energy, and PV with biogas. The electric power generated through the PV modules in the daytime is stored in the battery. At night it is possible to generate power from a biogas station; therefore, the consumer gains continuous power supply over the 24 hours. The subsequent hybrid system provides an optimized solution at an inherently decreased cost. It could be suitable for the electrification of the food market and the adjoining neighbourhood. The state of art technologies based upon the latest studies to incorporate double power sources seem to be an ideal solution in developing countries [95].

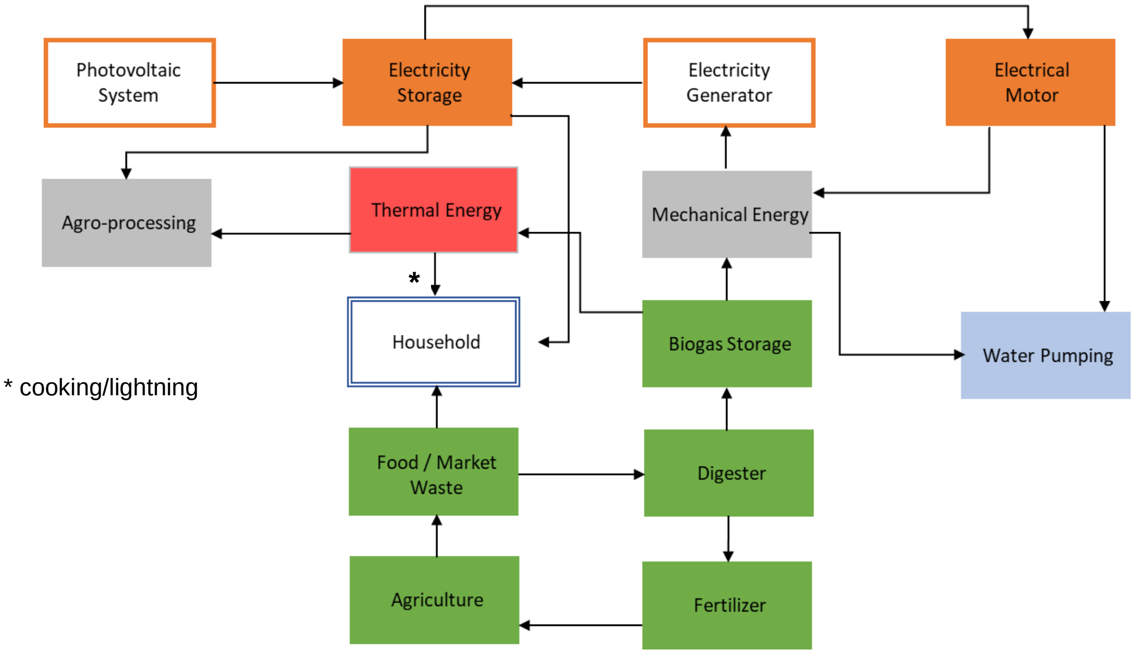


Fig. A.C. 2 - Suggested hybrid PV-biogas system.

Stability and durability are some of the most significant determinants when reflecting upon the implementation of decentralized RE sources for power generation. Over the past decades, the utilization of diesel generators has been a top choice for supplying energy in Ghana. The widespread notion of diesel electrical generation permanence is attributed to the preliminary inexpensiveness and uncomplicated fuel storage for installed plants. Despite that, long-term exploitation, fuel transportation, and, above all, volatile crude oil prices influence the operating and maintenance costs directly. In recent years, GHG emissions from fossil fuel combustion became an additional expense that enhances the exploration of power generation alternatives [96].

In this suggested system, the accessibility of energy may be utilized in diverse ways based on local demand, consequently presenting an attribute of flexibility. Following the route of the primary energy sources, it is achievable to track several trajectories of produced energy utilization (Fig. 2.3). The digester could be fed with waste from the local food market as well as household organic waste. Throughout the digestion phase, biogas and biofertilizer are produced in the digester. The former can be applied to create a thermal and then a mechanical form of energy used to feed the prime mover for the electric generator or in order to move mechanical appliances suchlike water pumps. The latter is used to improve the particular microbial processes to enhance nutrition access in a manner easily assimilated by the plants. The solar energy can take in charge also one part of the self-consumption of the digester [97].

Commonly, the alterations of solar energy production do not correspond to the time dissemination of the load. Hence, power generation systems direct supply of battery storage to reduce the time-distribution imbalance among the power load and PV generation and support the technical service or blackouts of the energy system [95]. Electricity generated through PV and stored in batteries is able to be recovered overnight. The utilization of the biogas system with PV–battery mitigates battery storage demand. An evaluation carried out globally suggests that a hybrid PV-biogas-battery system (exemplifies an economically reasonable adjustment within the significant CAPEX of autonomous solar panels system and biogas generator) is a secure power source [98]. Stability is part of the leading value propositions for this solution. The combined solar-biogas power generation systems are becoming a widespread alternative for remote districts or isolated power networks with lower energy demand. Due to the interconnected variety of biogas-solar energy supplies in some areas, the combined power system gives an incredibly stable source of electricity.

PV and biogas complement each other properties: CAPEX of PV installation is more expensive over biogas, operating cost (OPEX) of PV is respectively lower, maintenance and conservation provisions of PV are below the expenses as compared to biogas, biogas energy is obtainable for longer period of time during the day whereas accessibility of PV is largely conditional on solar radiation [99]. The possibilities of deriving power from hybrid setup have accelerated, and several PV–biogas–battery systems (with capacity coefficient in the span of 20–35%) occur all over the world [100].

Main bottlenecks and obstacles

As stated by Edjekumhene et al. [101], obstacles that have tumbled biogas distribution in Ghana involve unfavourable policies, non-accessibility of feedstock materials, inadequate financing structure, difficulties with public acceptance, deficiency of market, and scarcity of information. In regard to the government's low engagement of biogas undertakings, several private biogas enterprises have commercialized the methodology on solely business justification, above all attributed to biogas plants' capability to enhance sanitation [87, 92, 102].

Various research [88, 91] have exposed a considerable share of the biogas systems which weather do not operate correctly or are not operating at all. A frequent obstacle with biogas systems is their under-sized construction. At times it is a consequence of the ‘unsuitable’ design and structure of the digester as a result of insufficient knowledge. In some instances, the application of low-grade construction materials or lousy execution is the explanation for the biodigester breakdown. In such a situation, the contractor was lacking sufficient knowledge, expertise, and experience with establishing biogas systems. After a couple of years of operation, utilizing substandard construction materials can prompt leakage and deterioration of the biogas system. When high-quality construction materials have been applied, the whole system is assessed to have a lifespan of approximately 20 years. The abundant bio-waste sources, especially with regard to MSW in Ghana which can be adopted as raw material for biogas production to decrease the excessive dependence of wood- and fossil fuel, as well as to reduce further the GHG emissions is available. Ghana has a technical capacity to create approximately 280,000 biogas plants; however, only around a hundred plants were built. In Ghana, and globally in Africa, the spread of biogas technology turned out to be moderately successful. Week dissemination is associated with the disappointing approach of African authorities to promote biogas technology by a directed energy strategy, inadequate design and building of biodigesters, improper handling and absence of maintenance by operators. Besides, poor propagation approaches, absence of project supervision by facilitators, and weak control engagement by operators are additional challenges leading to a limited spread of biogas technology.

Inadequate maintenance is part of the important obstacles prompting systems failure. A biogas digester demands a limited amount of maintenance. At times, some small technical repair work is required, such as patching minor cracks and holes in the dome, ensuring proper gas links, and substituting the biogas balloon. Indeed, the construction company is usually not responsible for such support after putting a digester into operation. Consequently, several digesters are not operating correctly, and frequently, they do not operate at all. Nevertheless, a number of these structures can function adequately with occasional repairs (generally performed at a low expense) [103].

The scarcity of data gathering, assessment, and information distribution is considered as a limitation to AD technology in Ghana. Numerous institutional records remain confidential and collecting data is hindered by certain measures. Besides, research obligations are still not yet thoroughly embraced by academic and government bodies, seldom due to insufficient funds or inadequate plan of action. These harm biogas propagation and restrain cooperative research programs among industrialized and developing countries. The likelihood of technological alteration that could enhance the professional mindset and gratification for biogas facilitators will be downplayed. Notwithstanding the occurrence of a wide variety of market opportunities in Ghana, expertise has determined that local contractors have not yet seized the prospect of such possibilities due to a lack of capability and financial support to establish a persistent business plan of scholarly research [104].

Demonstration and trial period in Ghana started a couple of decades ago; however, according to reports, the majority of digesters built throughout that time manifested several malfunctions that disturbed biogas distribution projects [88]. This technology demanded several skills, crafts, community acceptance, and outlook for stable progress, which the users and recipients missed. Besides, plenty of biogas installations were private demonstration projects not desired by the users but instead tolerated.

Hence, conventional energy sources maintained to be favoured, and the interests of biogas plants have not been exploited. The large discrepancy in the overhaul acknowledges the role, relevance, and benefits of biogas dissemination on people's well-being, primarily those economically disadvantaged. Moreover, biogas technology has to overcome some obstacles like significant investment cost, legislative, political, and safety concerns, and pilot-phase complaints to guarantee that commercial biogas plants have been implemented. It is necessary to thoroughly involve and accelerate the propagation of biogas plants by creating explicit policies to foster and advance AD technology fully. Awarding subsidies and encouraging neighbourhoods to disseminate the biogas industry might resemble a milestone considering it could cause job formation and, above all, grant access to a source of reliable energy [78, 85].

Ghana – conclusions and recommendations

Numerous African nations have immense bio-waste sources which could potentially be utilised as the base material for methane generation by adopting industrial biogas plants. Nevertheless, as a result of various restraining constituents, these assets are under-used. This work intended to evaluate industrial biogas system which treats organic fraction from MSW, local food market, and other facilities, to recognise fundamental models which city of Kumasi could apply to acquire and propagate before-mentioned biogas system. Through the cooperation with the municipality, it was understood that the significant obstacles to implementation and development of an industrial biogas development are, most of all, communication with local stakeholders and mutual understanding of the discussed concepts. On top of that, the investigation exposed the limited presence of environmental policies, inadequate institutional structure, weak foundation, and a general absence of willpower to apply and perform renewable energy strategies and initiate challenging objectives. Utilising knowledge and expertise from more experienced nations like Germany or China, some key models could be distinguished.

The dissemination of industrial biogas systems requires the assistance of local and state authorities similarly to different areas. Prosperous development and supervision of industrial biogas systems demand not just technical expertise and knowledge but also critical consideration of financial, energy, and environmental measures.

Furthermore, the different university and research faculties region-wide need to enhance and concentrate study on the matter. Research ought to handle the issues from an interdisciplinary viewpoint and concentrate on creating reliable evidence to back policy declarations, applying case studies to review the financial, supply, and technical feasibility of industrial biogas systems. Ghana has to additionally support industrial biogas education and potential building projects and build interconnections linking research organisations and inherent receiver shareholders.

The business sector demands structural ability in the evolution of climate-smart undertakings that are able to be competitive on the global financial market. Hence, public-private bodies are required, so that the business sector and governmental bureaus comprehend each other's merits and complete their shortcomings. Finally, reliable environmental and sanitation political measures and their implementation and execution are vital to the realisation of industrial biogas plants, as well as the core to guaranteeing ecological integrity in Ghanaian cities.