Universität Kassel

Ph.D. DISSERTATION

Solar energy integration in agro-processing in the tropics: a case study of large and small-scale cassava processing.

Thesis submitted for the academic degree Doktor der Agrarwissenschaften (Dr. agr.)

Araba Amo-Aidoo

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Faculty of Organic Agricultural Sciences.

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Supervised by

Prof Dr Oliver Hensel.

Prof Dr Habil Barbara Sturm.

Dr Agra Joseph Kudadam Korese.

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Declaration

Declaration in accordance with § 8 of the General Provisions for Doctoral Degrees at the University of Kassel dated 14.07.2021.

1. I herewith give assurance that the submitted dissertation [Solar energy integration in agro-processing in the tropics; a case study of large and small-scale cassava processing]
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Nomenclature

APS	Agro-Processing Sector
ADDS	Advanced Dish Development System
A_o	External areas of heat exchange (m^2) ANFIS Adaptive Neuro Fuzzy Inference System
A_m	logarithmic mean area (m^2)
A_i	Internal areas of heat exchange (m^2)
BDA	Big Data Analysis
BC	Benchmarking Comparism
β	coefficient of thermal expansion (/°C)
Cp,	Specific heat capacity (kJ/kg °C)
CP, W	Specific heat capacity of water (kJ/kg °C)
CP, CS	Specific Heat Capacity of cassava slurry
CP, C	Specific Heat Capacity of cassava (kJ/kg °C)
CP	Champion Processor
CAADP	Comprehensive African Agricultural Development Programme
DEA	Data Envelopment Analysis
$\Delta\vartheta$	Difference in temperature (°C)
Q_{DEM}	Energy demand (kWh)
FP	Farmer Processor
FP	Farmer Processor
FAST	Functional Analysis System Technique
G_r	Grashof number
GPR	Gaussian Process Regression
GDP	Gross Domestic Product
Q_H	Heat loss (kW/m^2)
$\dot{q}_{tr, b}$	Heat transmission from the bottom of liquefaction tank
α	Heat transfer coefficient (W/ m^2 °C)
$q_{tr, li}$	Heat transmission from liquefaction (kW/m^2)

Q_{cond}	Heat loss from condensate (kW/m^2)
Δh_e	Heat of evaporation (kJ/kg))
$h_{i\,,}$	Heat transfer coefficient inside the column (kW/m^2)
IFAHP	Intuitive Fuzzy Analytical Hierarchy Process
LOGSIG	Log Sigma
LEAP	Long-range Energy Alternatives Planning
L	length (m)
MW	Mass of water (kg)
MRIO	Multi Regional Input Output
MCS	Mass of Cassava slurry (kg)
MCMC	Markov Chain Monte Carlo
MCDM	Multi Criteria Decision Making
M	Mass (kg)
OSD	Open Sun Drying
PPP	Photovoltaic Power Plants
PHL	Post-Harvest Losses
PCM	Phase Change Material
QFD	Quality Function Deployment.
r	Radius (m)
∏	ratio of a circle’s circumference and diameter (3.14159)
STD	Solar Tunnel Drying
SSF	Simultaneous Saccrifaction and Fermentation
SSA	Sub Saharan Africa
SFA	Stochastic Frontier Analysis
SES	Sterling Energy Systems
SAM	System Advisor Model
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
t_{ins}	thickness of insulation (m)
λ	Thermal conductivity (W/ m °C)
TBL	Triple Bottom Line
TANSIG	Tangent Sigma

K_p	Thermal conductivity of the tray material (kW/m °C)
V_{mix}	Volume of mixture; cassava, water, and cassava slurry (m^3)
WFC	World Food Conference

Preliminary remarks

This thesis is based on manuscripts and conference papers either published, accepted or submitted for publication in peer-review journals and are referred to in the text by their chapters as shown below:

> Chapter 3: Amo-Aidoo, A., Kumi, E. N., Hensel, O., Korese, J. K., & Sturm, B. (2022). Solar Energy Policy Implementation in Ghana: A LEAP Model Analysis. Scientific African, e01162. Doi.org/10.1016/j.sciaf.2022.e01162.
>
> Chapter 5: **Amo-Aidoo, A**., Hensel, O., Korese, J. K., Neba, F. A., & Sturm, B. (2021). A framework for optimization of energy efficiency and integration of hybridized-solar energy in agro-industrial plants: Bioethanol production from cassava in Ghana. Energy Reports, 7, 1501-1519. Doi.org/10.1016/j.egyr.2021.03.008.

Conference contributions during the doctoral study.

The various conference contributions achieved during the doctoral study have been listed below:

1. **Amo-Aidoo A.,** Hensel O., Korese J.K., Sturm B. (2019). Renewable Energy Policy Transition failure in Ghana**.** *Poster presentation at the 2nd International Conference on Energy Research and Social Science conference* in Arizona State University from the 28th to 31st May 2019.
2. **Amo-Aidoo A.,** Hensel O., Korese J.K, Sturm B. (2019). *Energy Audit, Process Optimization, and Renewable Energy Integration – Case Study Cereal Production SME. Herrenhausen Conference*- relations between climate extremes and sustainable development goals. October 9-11, 2019, Hannover, Germany.
3. **Amo-Aidoo A.,** Hensel O., Korese J.K., Sturm B. (2019). Strategies for promoting sustainable development in Africa through enhanced SDG 5 and SDG 15 implementation: The case of Ghana. *5th Annual FLARE meeting*. August 23-25, 2019. School for Environment and Sustainability, University of Michigan.

4. **Amo-Aidoo A.,** Hensel O., Korese J.K., Sturm B. (2019). Improving the implementation of Sustainable Development Goal 7 in Sub Saharan Africa through solar photovoltaic and thermal applications. *2nd Annual Sustainability and Development Conference*. October 11-14,2019, University of Michigan. I was unable to attend this conference due to funding.
5. **Amo-Aidoo A.,** Hensel O., Korese J. K., Sturm B. (2019) A Review of solar energy policy and applications In Ghana towards Sustainable Development Goal 7 And 13. *The Sustainability: Transdisciplinary Theory, Practice, and Action (STTPA) Conference* October 16 -18, 2019, in Mississauga, Ontario, Canada.

Thesis structure

The doctoral dissertation is presented and organized in 9 chapters as follows:

Chapter 1: Introduction

The first introductory chapter addresses the background and the issues related to integrating solar energy into the agro-processing sector in the tropics. This chapter presents the approach of the research methodology to achieve the specific objectives.

Chapter 2: State of the Art

In this chapter, current manuscripts relating to the study are presented.

Chapter 3: Methods, materials, and investigated factors.

All materials and methods related to this study are presented in a tabulated form for easy reference.

Chapter 4: Solar Energy Policy Implementation In Ghana: A LEAP Model Analysis

This chapter presents all literature reviews related to electricity status, solar energy policy, and its application in Ghana in a review manuscript. Scenarios were modelled using LEAP software to demonstrate the effect of promoting or demoting solar energy integration in the national energy mix.

Chapter 5: A framework for optimising energy efficiency and integrating hybridized-solar energy in agro-industrial plants: Bioethanol production from cassava in Ghana.

The Functional Analysis System Technique (FAST) was introduced for systematically translating plant-wide energy requirements into detailed functional and performance design criteria for energy efficiency, optimization, and solar energy integration. This chapter discusses the result of the large-scale case study for optimization. The framework developed presents an invaluable tool for optimizing energy efficiency and integrating solar thermal and solar photovoltaic energy sources for the agro-industry sector.

Chapter 6: General discussion

This chapter discusses the key results, challenges, and related problems from the described experiments in this study and recommendations for further research.

Chapter 7: General Conclusion

The conclusion of the study is presented here. Also, this chapter discussed the general issues and challenges while experimenting with this study.

Chapter 8 & 9: General recommendations and General references.

The recommendations and references are presented in these chapters.

Chapter 10: Summary

The overall introduction, literature, methods, discussions and conclusion of this study is summarised in this chapter.

1. GENERAL INTRODUCTION

Agro-processing is key to reducing post-harvest losses. Agro-processing is defined as a set of techno-economic activities applied to all the products originating from the agricultural farm, livestock, aqua cultural sources, and forests for their conservation, handling, and value-addition to make them usable as food, feed, fibre, fuel, or industrial raw materials [12]. Processing can be sophisticated (relying on industrial plants and machinery) or simple (depending on the sun or indigenous small-scale processes). The industrial-scale processing is mainly dependent on electricity, whiles the small-scale applications are mostly not. However, the quality and duration of the processing are improved with the availability of electricity.

Most agricultural produce can be processed into so many products. In Ghana, grains are usually processed into flours, tubers into chips, fish into powders and leaves into powders in the food sector. Some industrial plants use agricultural produce as their raw material, such as biofuel plants. Other uses also include animal feed and biogas production.

This study focuses specifically on cassava processing as a case study crop, although findings are replicable and scalable to other crops. Cassava processing in Ghana is mainly by drying the roots and milling them into flour. The peels, leaves and stems serve as animal feed. However, the leaves are also in some sauces for human consumption. The few large-scale processors use cassava for starch and bioethanol production. However, the transition to bioethanol is increasing, similar to China [13].

1.1 Problem statement

The contribution of the agricultural sector to Ghana's economy has been declining from 20.98% (2016) to 17.31% (2019) of GDP [3]. The contribution of the agriculture sector to Ghana's economy has been declining from 20.98% (2016) to 17.31% (2019) of GDP.

Electricity supply and access challenges to rural farming communities have been cited as a factor constraining the growth of the Agro sector as this increases post-harvest losses and value addition to crops.

Globally, solar energy is growing in prominence as a reliable alternative and sustainable energy source. Arguably, there is potential for solar energy to be integrated into Ghana's agro-processing sector as an alternative source of energy to support the growth of the agriculture sector.

This study specifically focuses on assessing the potential of integrating solar energy in Ghana's Agro-Processing Sector (APS), more minimal and large-scale cassava processing.

1.2 General objective

The main objective of this thesis is to investigate optimum strategies for integrating solar energy into the APS using cassava as a case study in Ghana.

1.2.1 Specific objectives

i. To conduct a field and desk surveys on solar energy and Agro-processing in Ghana.

ii. To conduct a numerical and experimental study of the power demands of the various units for selected case studies on cassava.

iii. To develop a novel framework for large scale solar integration.

The following **research questions** were formulated to address the objectives above,

i. Under what scenarios and circumstances can solar energy be a good choice for integration in cassava agro-processing?

ii. Can a novel solar integration framework be developed for the processing of cassava?

1.3 Overall research methodology

Below is a description of the strategies for achieving the objectives:

I. The desktop study of the electricity situation and the status of solar energy in Ghana. LEAP was utilized to model the scenarios for solar implementation.

II. An extensive nationwide field survey was conducted to determine the status of the various agro-processing plants. 21 agro-processors were visited from 8 regions in Ghana.

III. A stratified sampling method was utilized to select the two case studies. Detailed energy audits were used to determine their respective overall load profiles, followed by their individual unit profiles.

IV. In the large-scale scenario, process optimization was done after the detailed field audit before the solar system design. A framework for optimization of energy efficiency and integration of hybridized-solar energy in the sector was developed. A bioethanol plant from cassava in the Volta region was used for this case study.

1.4 **References**

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2 STATE OF THE ART

This chapter presents the review of related literature on cassava botany, processing and nutritional value, global and national perspective on agro processing of cassava, and the application of solar energy for processing in general and cassava in particular. Further literature is provided on processing methodologies such as Multi-Criteria Decision Making (MCDM) matrix,, is presented. The relevance of solar modelling software such as the LEAP and the System Advisor Model (SAM) is also shown in this chapter. The national context is also further reviewed.

2.1 Agro-processing of cassava

For Bioethanol production, the cassava root is the most commonly used part [1], although the stem [2] and peels (response surface methodology) [3] can be used as well. However, the stem uses relatively more energy for the production process than the roots.

The four main processes employed in bioethanol production from cassava roots are peeling, rasping, liquefaction and fermentation. Recent studies use Simultaneous saccharification and fermentation (SSF) to reduce the cost of production, save time and reduce the net processing energy. However, there are challenges associated with simultaneous saccharification and fermentation (SSF) usage, namely reduced yield due to the varying fermentation and saccrifaction temperatures, 35°C and 50°C, respectively [4]. The application of thermo-tolerant yeast combats this challenge [5]. Pre-hydrolyzation also fights the same challenge [6].

Also, traditional batch loading requires high mass and heat transfer which inhibits SSF. According to the literature, fed-batch loading where the substrate is added at different times resolves this challenge[7,8]. Inhibitors formed in saccrrifaction can also be eliminated by adding alkaline and some hemicellulose [9].

Integrating succinic acid production in a bio refinery co-producing bioethanol is a potentially viable bi-product with economic and environmental benefits [10]. Drying affects the quality of cassava chips [11]. Fermentation, blanching, and drying temperature also affect cassava flour's functional and chemical properties[12]. Different pre-treatments (fermentation and blanching) affect the drying characteristics of cassava chips using sun and solar dryers [13,14] . Other factors such as drying kinetics, temperature, air velocity, and flow rate affect dried cassava chips [15,16] .

Before processing, several models such as Multi-Criteria Decision Making Matrix (MCDMM), Functional Analysis System Technique (FAST) diagrams, and models are applied to standardize application protocols. Also, essential steps such as process optimization and energy efficiency are critical.

2.2 Cassava Botany, production, processing, and nutritional value

Cassava (Manihot esculenta), also known as cassava manioc, yuca, macaxeira, mandioca, aipim, and agbeli, is a woody shrub native to South America of the spurge family, Euphorbiaceae [17]. It is primarily cultivated in Africa, Asia, and South America [18,19]. In 2018, the world cassava root production reached a record of 277.1 million tonnes, of which Sub-Saharan Africa (SSA) contributed 161 million tonnes [20]. West Africa is the leading cassava roots producer globally among Brazil, Thailand, and Indonesia[21].

Continuing strong growth in food demand for cassava reflects the critical role cassava plays in the diets. Cassava has exceptional capacity in that it adapts easily to climate change and tolerates drought conditions and low soil fertility [22]. In Ghana, it is primarily cultivated in the savannah region. The growth rate in food demand also stipulates that cassava will maintain its importance in regional diets as Sub-Saharan Africa continues to urbanize and increase its share of processed food products for consumers in the countryside and the cities. Increased cassava production can be exploited by establishing starch-based industries [23].

Cassava has food and non-food uses. The non-food uses are mainly for animal feed and starch. Cassava is also a cheap but good energy source for the human diet; cassava root is 80 % starch. However, it is mainly used for industrial purposes in Asia[24]. Cassava root is principally used for industrial processes because no significant biotic constraints affect productivity [24-29]. The most common industrial use is ethanol production for the pharmaceutical and brewery sector. It is also used in starch production.

Starch is one of the products of cassava. Starch is an important raw material in the fermentation industry for producing ethanol, which can then be used as renewable biofuel or as a basis for food, drink, and pharmaceutical products. Several studies have been conducted on the feasibility and use of cassava in bioethanol production. Although Taioba (*Xanthosoma sagittifolium*) is a subsistence agriculture plant with high starch content [30], cassava has higher starch content and has been more exploited.

Fresh cassava roots contain high moisture content of 60–65% w.b, which causes deterioration during storage [31]. The roots are usually dried or processed into food products to increase storage stability. However, the microstructure is significantly affected by increasing temperature [32].

Pullulan, one of the cassava products, is a biopolymer of high commercial importance and utility [33]. Pullulan, primarily available in powdered form, can also be formulated into thin films. These films have numerous applications in the food, pharma, and healthcare industries. The most popular and commercially successful application of pullulan films is in Listerine mouth freshener. [34]

In Ghana, like most African countries, it is a staple crop forming a prominent part of the diet. Dishes such as fufu, Akple, and gari are prepared using cassava roots. The cyanogenic (bitter) type contains hydrocyanic acid, and this is removed from cassava roots and leaves by using a mix of complex traditional methods and modern technologies during food processing and preparation, such as a combination of "blanching ⁻ dry heating ⁻ wet heating", with an average reduction of 81 % of these compounds. The cassava root is peeled, washed, and grated/rasped for Gari making. This step is followed by fermentation activity to produce organic acids and reduce cyanogenic potential. The pulp is dewatering to reduce the water content in the cassava. The cassava cake is then de-lumped and sieved before frying or roasting. Depending on the dryness level, the gari produced can be stored for not less than three months.

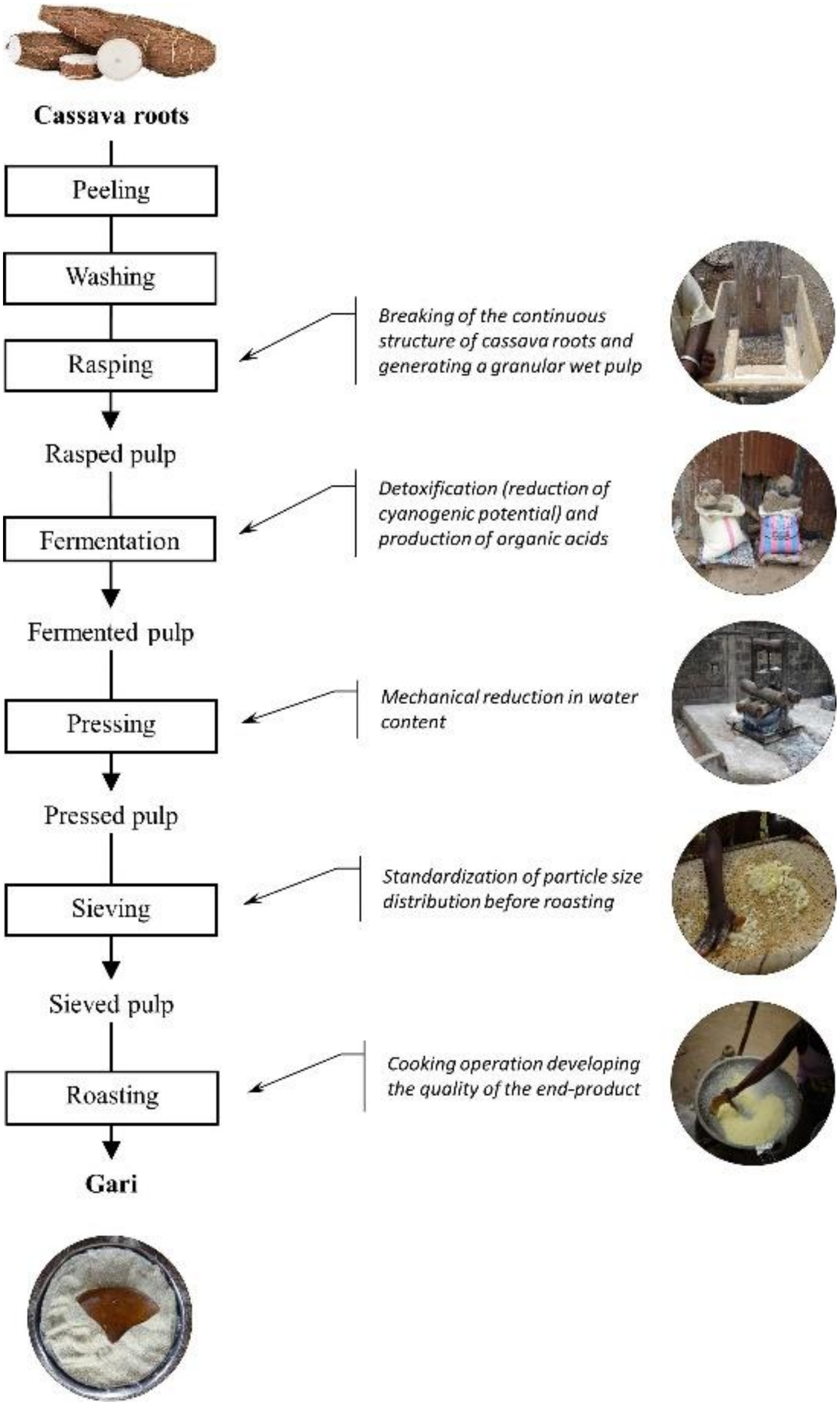

Fig 2 1 Process diagram to transform cassava roots into gari [35].

Table 2 1 Preferred characteristics of fresh roots and food products and their frequencies, elicited during pairwise ranking of fresh roots, gari, eba, and fufu by champion processors (CP) and farmer–processors (FP) in Nigeria [36].

Fresh roots for gari High *gari* yield	**Freq. %**	**Product**		**Freq. %**		**Product**	**Freq. %**	
	CP	**FP**		**CP**	**FP**		**CP**	**FP**
High root yield								
Large size			*Gari*			*Eba*		
Low water content	68	37	Colour (white/ butter/not brown)	73	76	Good Appearance	86	68
Easy to peel	8	38	Heavy/dense	52	61	Heavy	48	15
Dry skin	43	28	Smooth	52	61	Smooth	41	30
Gari quality	43	50	Good taste	35	38	Stretchable	29	28
Smooth skin	24	13	Crunchy	28	20	Firm	20	34
Brighter *gari*	22	17	Swells well making eba	23	8	Good taste	18	24
Heavy/dense	18	37	Good appearance	22		Swell well when prepared	15	2
Fine appearance	13	2	Neat (clean)	22	17	Neatness (clean)	14	19
Darker skin colour	8	14	High Yield	2		Mouldable	8	22
	1	3				Aroma	5	4
						Preservable	5	
						Starchy		14
	47	33	Bright	38	55	Good appearance	37	
	41	49	Good uniform granule size	32	3	Non-sticky (to hands)	28	

Fresh roots for gari High *gari* yield	Freq. %	Product		Freq. %		Product	Freq. %	
	CP	**FP**		**CP**	**FP**		**CP**	**FP**
	38	53	Fine appearance	29	1	Stretchable	25	
	33	13	Swelling when making eba	29	13	Soft	20	
	1	4	Dry	27	16	Swell well when prepared	15	
	8		Should accept oil	16	1	Heaviness	14	
	7		High *gari* yield	15	14	Sticky	14	
	5		Sell fast	10		Firm	14	
	3		Should provide good *eba*	8		Bright	9	
	2	10	No lumps	4		No dull colour	9	
	1		Heavy *gari* (dense)	3	44	High eba yield	9	

The leaves are also harvested and processed for human consumption in sauces and salads [37-41]. A recent study in Argentina showed that the concentration of cyan glycosides in fresh leaves ranged from 242 to 401 ppm, with the highest values recorded in Mico and Pomberí varieties. The mean essential amino acid content was 44 %, with a predominance of lysine (5.92–7.02), phenylalanine (5.62–7.13), and leucine (7.35–9.30 g/100 g protein). The Campeona variety has the highest concentration of amino acids.

Cassava leaves are used in baking as well due to their protein content. The stems are used as animal feed as well as seedlings for planting. They are also used as animal feed for monogastric animals. Their peels potential for bioethanol production has been considered economically viable due to its chemical properties, relatively low cost, availability, and renewable nature Click or tap here to enter text.[42,43]. Additionally, bioethanol from cassava peels pulp is a value-added alternative for cassava pulp management and reduces the environmental impact of cassava processing [44].

Beetle *Teretrius* (*Teretriosoma*) *nigrescens* can protect dried cassava chunks from attack by the larger grain borer during storage [45] in pest and insect control. Other practices like harvesting cassava from moist, less compacted soil result in lower damage (21.6%) than from dry, compacted soils (44.6%) [46].

2.3 Energy auditing and efficiency

Four principal energy efficiency evaluation methodologies: Stochastic Frontier Analysis (SFA), Data Envelopment Analysis (DEA), exergy analysis, and Benchmarking Comparison (BC), are commonly used [47] in audits. However, the DEA approach is the most recommended because it is the most frequently used methodology, with over 144 published scholarly articles by 2015 [48]. This methodology is also practically and technically feasible, given limited financing as established in the other case studies [49-51].

Energy policy plays a crucial role in the advancement of auditing practice globally. Countries implementing energy audit policies, especially in the commercial and industrial sectors, have advanced considerably in providing reliable supply to meet the stipulated demand. A summary of these policies, countries, status, and jurisdiction can be found in table 3.

Table 2 2: Summarized policies on energy efficiency from selected countries [52]

Country	Policy	Status	Year	Jurisdiction
Australia	Retailer energy efficiency scheme	in force	2015	South Australia
	Hydrofluorocarbon (HFC) phase-down	in force	2018	National
	Improving the energy and emissions performance of buildings	in force	2019	National
	Commercial building disclosure program	in force	2011	National
Germany	3rd National Energy efficiency plan	in force	2014	National
	Compulsory energy efficiency audits in large companies		2015	National
France	Mandatory energy audits	in force	2014	National
Italy	Legislative Decree 4 June 2013 (DL 4/6/2013)-Transposition of the European directive 2010/31/UE on the energy performance of building	in force	2013	National
European Union	EU Energy Efficiency directive(2012/27/EU)	Ended	2012	International
Russia	Energy audits and Energy passports	in force	2010	National
	Resolution no. 18 - Establishing Energy Efficiency Requirements for buildings and structures	in force	2011	National
Canada	Technology Innovation and Emission Reduction Regulation	in force	2020	Alberta
Turkey	YES-TR green energy certificate	in force	2020	National
	Green certificate regulation for buildings and settlements	in force	2017	National
Morocco	Decree n. 2-17-746 on Mandatory energy audits and energy audit organizations	in force	2020	National
	Decree n. 2-18-165 on mandatory energy audits	in force	2019	National
Sweden	Law on energy mapping in large companies	in force	2016	National

Generally, the regulations in Europe to launch programs in energy efficiency has resulted in considerable savings in the region. Specific actions such as the decommissioning of nuclear power projects as stipulated in the Energy Reform Policy (ERP) by Germany, the Italian white certificate scheme [53], and the UK's industrial energy efficiency efforts [54] can be replicated in other regions to catalyse energy optimisation.

Following the lead of Morocco and Turkey, other countries in Africa could also enact policies to push industrial energy efficiency. The Agro Processing Sector should be targeted specifically to reduce electricity demand which is the principal prerequisite for solar energy integration. The Renewable Energy Master Plan, which is an extension of the Renewable Energy Act, would stand better chances of achieving its target if energy auditing becomes an obligation, especially in the commercial and industrial sectors. Like the Latvian example [55], these schemes should be monitored and evaluated for continuous improvement.

2.4 Process optimization

Process optimization is an essential step before solar energy integration. In most studies that process optimization was conducted, the amount of energy required for the process was reduced. The proportion of reduction depended on the scope of the processing. In Bio-ethanol production, the Simultaneous Saccharification and Fermentation (SSF) significantly reduced production's energy requirement and cost as separate saccharification and fermentation processes were merged as one. However, there are challenges associated with using SSF, namely reduced yield due to the varying fermentation and saccharification temperatures, 35 °C and 50 °C, respectively [56] The application of thermo-tolerant yeast has proven to combat this challenge [57]. Pre-hydrolyzation also combats the same challenge [58]. Also, traditional batch loading requires high mass and heat transfer, inhibiting SSF. According to the literature, fed-batch loading where the substrate is added at other times resolves this challenge [59, 60]. Inhibitors formed in saccharification can also be eliminated by the addition of alkaline and some hemicellulose [61]. With the significant challenges combated, the adoption of SSF is highly recommended.

2.5 Solar in Agro-processing

The amount of energy by the sunlight striking Earth in 1 hour is equivalent to the world's energy consumption for one year [62]. Solar energy is a clean form of energy and a suitable energy source for green processes such as food-related processes; it has recently attracted significant attention from industry and academia. [63–64]. Solar energy can be applied to different technologies. The adoption trends of solar energy technologies rely on the policies [65]. The general overview of solar energy is summarised in fig 2.

Integrating solar photovoltaic energy into the Agro-processing sector is technically and economically feasible in several case studies [66–67]. Technical efficiency can be further improved with dye-sensitized solar cells (DSSCs), perovskite solar cells, and organic photovoltaics[68]. Finite-difference time-domain (FDTD) for increased conversion efficiency of solar energy absorption of hybrid solar cells can be further improved [69]. Solar food processing is an emerging technology that provides good quality foods at low or no additional fuel costs. Several solar dryers, collectors, and concentrators are currently being used for various steps in food processing and value addition [70, 71].

Despite the significant advantages, particular attention has not been paid to the Agro-processing sector. Electricity supply and reliability continue to be a hindrance to the Agro processing industry. Farmers continue to face challenges with electricity inaccess. Most farming communities are located on the outskirts of the rural areas; hence the challenge of electricity impedes the efforts in processing and storage, making farming uneconomical.

A Spatio-temporal analysis approach in a study in Sudan confirmed the successful integration of solar energy in a small-scale processing scenario [72]. A detailed design and comprehensive numerical analysis of a hybrid Geothermal-Phase Change Material (PCM) flat plate solar collector showed that the efficiency of hybrid geothermal PA-FPSC is 20.5% higher than conventional flat plate solar collector when the mass flow rate is at 0.02 kg/s [73]. Prototype hybrid Photovoltaic Thermal (PV – T) solar dryer aided with Evacuated Tube Collector (ETC) in India reveals that the quality of hybrid dried cassava is better in terms of physical and chemical compositions than sun-dried cassava[74].

A multi-objective optimization approach to optimize economically and environmentally the implementation of solar photovoltaic systems is impactful[75]. Solar power is competitive and would fare well in hybrid schemes, and its performance should be encouraged by stakeholders and regulators in Kosovo [76].

2.6 System Advisor Model (SAM)

Although there are several software used in solar energy system design, the System Adviser Model (SAM,formallycalledthe Solar Advisor Model),

is key in predicting the long-term techno-economic performance of energy systems that rely on stochastic variables like solar radiation and wind [77]. The software can also model industrial process heat from the parabolic trough. A more detailed description of SAM can be found in [78-80]. Concentrating solar power modelling details may also be found in [81–83].

Two different commercial dish/Stirling systems, SES (Stirling Energy Systems) and WGA-ADDS (WGAssociates – Advanced Dish Development System), are modelled using the System Advisor Model (SAM) modelling software in designated settlement areas in Turkey. Although Turkey is located in a place called “the sunbelt” where solar energy technologies can be used, there is no advanced application of these systems. Stirling dishes have strong potential in this region and are therefore highly recommended [84].

Solar central receiver systems characterization and optimization using a numerical model combining the Monte-Carlo ray-tracing optical model, a simplified receiver heat transfer model, and a cost model based on the System Advisor Model (SAM) was studied. It was found that the general formulation of the model and broad range of values of the investigated parameters provide a universal predictive capability for studying the techno-economic performance of concentrating solar thermal systems [85].

Another study was conducted to validate SAMs modelling of Concentrated Solar Power Plants. It was concluded that the code needs further development, especially for the solar field and receiver of the solar tower modules and the thermal energy storage. It was supposed that validation of models and sub-models versus high-frequency data collected on existing facilities, for both energy production, power plant parameters, and weather conditions, is necessary before using the code for designing novel facilities. [86]

In a study, solar energy for milk pasteurization proved successful using a flat plate collector, heat exchanger, and solar water heating system [87]. Other studies on milk pasteurization using a Fresnel Paraboloid concentrator with cavity receiver in India with a capacity of about 20,000 to 30,000 l of milk daily, resulting in savings of 80 l to 100 l of furnace oil [88]. Solar Cabinet Dryer with forced circulation has been used to dehydrate and develop value-added products from locally grown fruits, vegetables, leafy greens, and forest produce. Drying under simulated shade conditions using a UV-reducing Blue filter helps retain nutrients better [89]. The techno-economic potential of two different photovoltaic power plants (PPP) (i.e., PV-only and PV-Battery) systems under three other climatic conditions in Ghana were presented. SAM was used to model a 20 MW system at Wa, Sunyani, and Nsawam to assess their technical and economic performances. In general, the northern section (Wa) was the best location for developing large-scale solar in Ghana. [90]

This study used SAM to develop technical performance and energy generation cost estimates for different parabolic trough designs. The other plant designs include two solar-only plants (differing in solar multiples) without storage or hybridization, one solar-only plant with a storage capacity of 4 h, and one solar trough plant integrated with natural gas hybridization [91]. A comparative financial analysis for the standalone solar photovoltaic system was also performed using the SAM. System advisor model analysis resulted in a positive net present value of $306.45 and a Levelized cost of the energy value of $0.15/kWh. The environmental analysis revealed net CO_2 mitigation of 104.59 Tons, equivalent to an earned carbon credit of $2090.31 from the hybrid system [92].

2.7 Long-range Energy Alternatives Planning (LEAP)

LEAP is a scenario-based energy-environment modelling tool for energy policy analysis and climate change mitigation assessment. LEAP can be used to track energy consumption, production, and resource extraction in all sectors of an economy, as well as account for GHG (greenhouse gas) emissions from energy demand and conversion [93-95]. LEAP model consists of three blocks of programs: energy scenarios, aggregation, and the environmental database [96, 97] used to model energy scenarios. LEAP can be applied at different scales ranging from cities and states to national, regional, and global applications [98]. Many researchers have established LEAP has as a good accounting tool for the energy demand/supply model by providing advantages such as being easy to use and inputting the data set [99–102]. Another advantage of LEAP modelling is that it allows users to build energy forecast systems based on existing energy demand and supply data, prepare and compare long-run scenarios, and compare results with different methods. This comparison helps identify those energy policies that have better effects on energy conservation, greenhouse gas reduction, or other attributes [103]. Additionally, LEAP modelling facilitates the creation of environmental scenarios [104].

With the assistance of the LEAP (long-range energy alternatives planning) energy modelling tool, the study reveals that energy consumption and GHG emissions of the iron and steel industry can be lowered significantly if the necessary measures are implemented [105]. The long-term greenhouse gas mitigation and economic impacts of integrating bioenergy from cassava residues into a national energy mix based in South Africa were assessed using Long-range Energy Alternatives Planning (LEAP) models for three integration schemes. The bioenergy exemplifies sustainable national bioenergy models for enhancing low-carbon economies [106].

The modelling method with Long-range Energy Alternatives Planning System (LEAP) software is implemented with the interpolation with growth, linear forecast, exponential forecast, and logistic forecast upon two projection scenarios of business as usual (BAU) and with current government policy in Indonesia [107] to forecast for electricity generation. LEAP has been applied in Austria and Bulgaria as a guideline for validating new modelling approaches that link energy policy decision tools to the global biophysical and socioeconomic constraints [108].

Electricity demand and supply forecasts are essential for determining solutions to the problems in the electricity sector, such as power outages. The Long-range Energy Alternative Planning (LEAP) modelling tool was used to project electricity demand and supply for 2040. As a result of the economic challenges faced by Nigeria, the Energy Conservation scenario was found to be the most realistic path to providing an uninterrupted power supply [109].In the Chinese case study, LEAP suggests that the Chinese government should consider the energy adjustment[110]. LEAP has been used to forecast electricity demand for the target year 2030 for the state of Maharashtra (India). In Pakistan, LEAP illustrates the policy implications of the model for futuristic power generation and environmental policies.

2.8 References

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3 METHODS, MATERIALS, AND INVESTIGATED FACTORS

This thesis presents a methodological approach to integrating solar energy into the agro-processing sector (APS) in Ghana using cassava as a case study as a solution to reducing post-harvest losses. The rationale behind this study is to integrate solar energy into the APS due to the challenge of energy access or stability of electricity from the national grid for agro-processors, the high cost of diesel and or gas for generators, and unhygienic conditions of open sun drying.

The experimental layout and procedures for each quality analysis are described in detail in the individual articles in Chapters 2,4-7. Thus, this chapter gives a tabulated overview of the materials and methods used in this study and the investigated factors together with related articles applied in Table 3-1.

3.1 National context

In total, 21 Agro-processors in eight regions of Ghana were visited in 2018. They were then categorized into large and small-scale enterprises according to the boundary conditions in table 4.

Table 3 1: Categorisation of enterprises / plant [197]

Scale	**Boundary condition**
Large	employ from 30 employees with fixed assets of up to US$1million.
Medium	employ between 6 and 29 employees with fixed assets of US$100,000.
Small	not more than five employees have plant and not exceeding US$ 10 million.

In table 3 2, most of the food processors were located in Ghana's eastern region (also known as the food basket). A few large-scale plants were also scattered in the industrial area in the

Greater Accra, Northern, and Volta regions of Ghana. Some farmers had formed cooperatives that processed their products together. Others also sold their products to medium and large-scale processors. Similar cooperatives formed in the agricultural sector have aided the integration of solar energy in the industry [198].

Table 3 2: Summary of enterprises visited during the fieldwork.

Size of Enterprise	**Location**	**Energy Source**	**Processing product**
Large scale	Nsawam - Eastern region	Grid connect electricity, diesel generator	Coconut, mango, pineapple, and watermelon
Large scale	Nsawam - Eastern region	Grid connect electricity, diesel generator	Coconut, mango, pineapple, and watermelon
Large scale	Nsawam - Eastern region	Grid connect electricity, diesel generator	Mango and pineapple
Large scale	Akuse-Eastern region	Grid connect electricity	Rice
Large scale	Tema - Greater Accra region	Grid connect electricity, diesel generator	Cocoa
Large scale	Tema - Greater Accra region	Grid connect electricity, diesel generator	Tomatoes
Large scale	Bawjiase - Central Region	Grid connect electricity, diesel generator	Cassava
Large Scale	Adeiso - Eastern region	Grid connect electricity, diesel generator, Solar photovoltaic, and biogas.	Mango, pineapple, coconut, bananas, and papayas
Large scale	Akuse in the Eastern region	Grid connect electricity, diesel generator	Banana
Large scale	Hodzo - Volta region	Diesel generator, biomass	Cassava
Large scale	Gushie - Northern region	Grid connect electricity, diesel generator	Mango
Large scale	Kintampo - Brong Ahafo	Sun drying	Cocoa

Medium-scale	Nsawam - Eastern region	Grid connect electricity, diesel generator	Coated nuts (Nkatie Buger)
Medium-scale	Tamale - Northern region	Grid connect electricity	Soya beans
Medium-scale	Tampion - Northern region	Sun drying	Alefu, Ayoyo, Okra
Medium-scale	Axim - Western region	Fuelwood	Fish
Medium-scale	Karaga- Northern region	Mechanical	Balanites, Sesame, moringa, Baobab
Small scale	Tamale- Northern region	Grid connect electricity, sun drying, fuelwood	Millet, Maize, Sorghum
Small scale	Tamale - Northern region	Sun drying	Soya Beans
Small scale	Tamale - Northern region	Grid connect electricity, fuelwood	Shear
Small scale	Salaga- - Northern region	Fuelwood	Groundnuts
Small scale	Kasalugu - Northern region	Grid connect electricity, diesel generator	Fonio

The primary energy source in all scenarios was electricity from the national grid. The large-scale processors mainly relied on grid-connected electricity with diesel generators as backup. However, 16% of them utilize other energy sources, including solar energy. The medium-scale enterprises had 60 % of them relying on other sources, including solar energy. The alternative energy in the small-scale sector was mainly from open sun drying, which was 80%.

Fig 3 gives a graphical representation of the current energy status in the Agro-processing sector and the scenario developed with the study. The primary source of the present baseline scenario is a grid that connect electricity with diesel generator backup. Some plants, however, have other sources such as fuelwood, biogas systems, solar photovoltaic systems, and the open sun. In this study, the reliance on electricity from the grid and diesel generators was reduced whiles hybridized solar photovoltaic and solar thermal systems increased in the overall generation mix. Carbon emissions will also be significantly reduced.

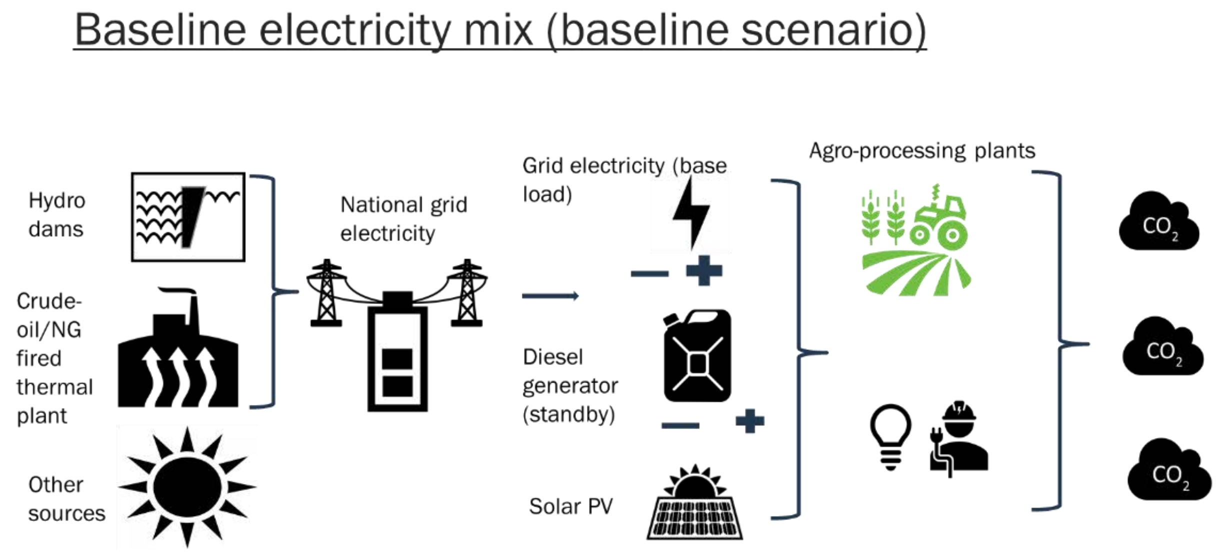


Fig 3 1: Baseline electricity mix scenario in the agro-processing sector.

Table 3 3: Materials, methods, and investigated factors related to the current study.

Methods (i) / Investigated factors (iii)	Chapters
Low Emissions analysis Platform (i)	2,3
Framework development (i)	4,3
The goal-setting modeling (iii)	4,4,1
Industrial plant modeling (iii)	4,4,2
Information modeling(iii)	4,4,3
Energy efficiency modelling (iii)	4,4,4
Energy integration modeling (iii)	4,4,5
Data modeling and analysis (iii)	4,4,6
System Advisor Model (i)	4,4,6,1
Thermal optimization (iii)	4,4,6,7
Data interpretation model (iii)	4,4,7
Functional Analysis System Technique (i)	4,6,2
Site visits (iii)	4,5
Energy auditing (iii)	5
Solar drying experiments (iii)	4,5
Site visits (i)	6
Dryer fabrication (i)	6
Multi-criteria decision-making matrix (i)	6
Stratified sampling (iii)	2
Microbial testing (i)	6,3,4

4 SOLAR ENERGY POLICY IMPLEMENTATION IN GHANA: A LEAP MODEL ANALYSIS

Amo-Aidoo, A., Kumi, E. N., Hensel, O., Korese, J. K., & Sturm, B. (2022). Solar Energy Policy Implementation in Ghana: A LEAP Model Analysis. *Scientific African*, e01162.

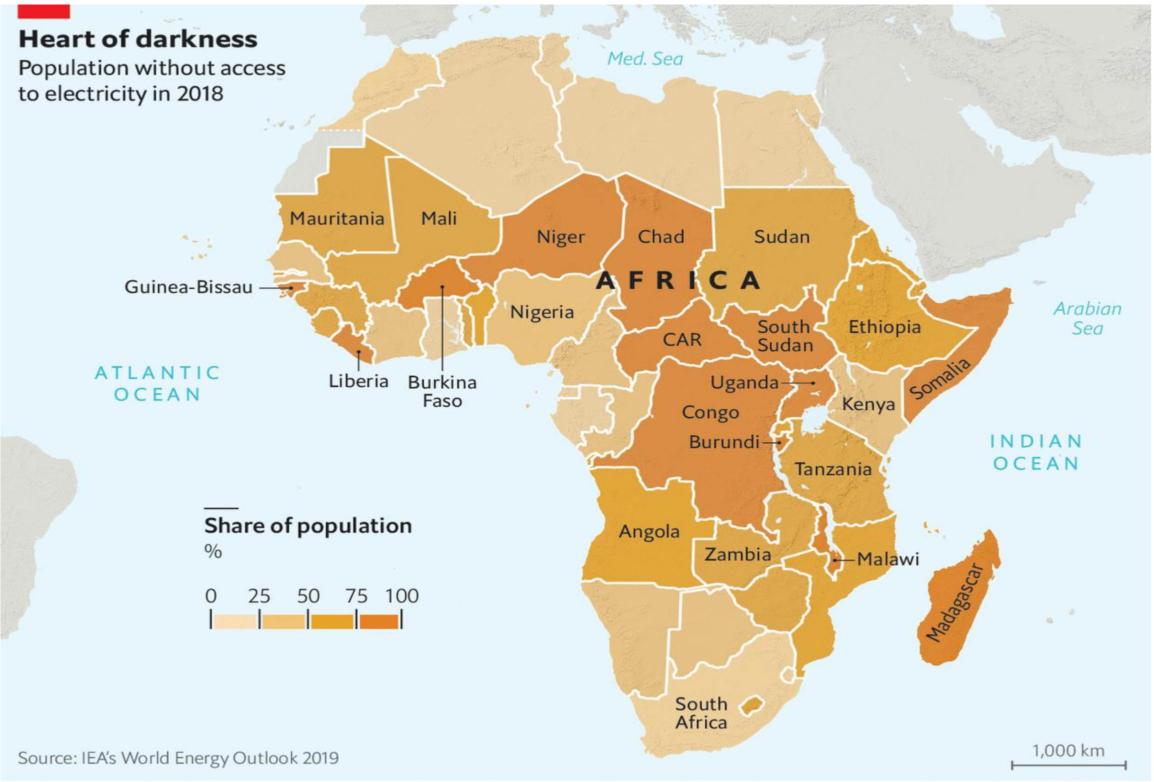
Abstract

Current global climate change mitigation programs have been unable to meet the Paris Agreement's targets, and Ghana's situation is no exception. There is, therefore, an increased impetus for intensification of renewable energy deployment programs with an emphasis on solar energy as it constitutes about 90 % of Ghana's installed renewable energy generation capacity. The study presents an evaluation of how renewable energy policy can drive solar energy development in Ghana. Electricity demand scenarios were designed using historical data from 2000 - to 2018, after which projections were made to 2030 based on the average year-on-year growth rate. Of the three consumption (demand) categories, residential consumption experienced a sharper growth rate in comparison with the particular load tariff, non-residential, and street lighting sectors. On the supply side, the low, moderate, and visionary supply scenarios had increased solar penetration of 5 %, 10 %, and 15 %, respectively, in the installed generation capacity. Appreciable gains were made in the low and moderate transition scenarios. However, the visionary supply scenario can meet the renewable energy target by 2030 with solar energy leading to universal access to electricity while offsetting over 13 million metric tonnes of carbon dioxide in the process.

Keywords: LEAP, electricity demand, supply scenarios, carbon emissions

4.1 Introduction

Although 411 million of the global population gained access to electricity between 2010 and 2018, over 620 million people could still be without access to electricity by 2030, according to the Tracking SDG 7: The Energy Progress Report 2020 [1]. Sub-Saharan Africa (SSA) alone had about 548 million people who lacked access in 2018. Electrification efforts have fallen behind population growth in most SSA countries, including Burkina Faso, the Democratic Republic of Congo (DRC), and Niger, as presented in Fig. 1 [2]. Like most developing countries in SSA, Ghana has electricity access and reliability challenges, despite the 82.5 % electricity access rate the government reported at the end of 2018 [3]. These challenges have impeded economic growth in all sectors of the economy.



Heart of darkness
Population without access to electricity in 2018

Source: IEA's World Energy Outlook 2019

The Economist

Fig 4 1: Overview of electricity access in Sub-Saharan Africa.

The energy tree presented in Fig 4 2 shows Ghana's installed electricity generation plants as of 2019, revealing that the primary sources of electricity generation in Ghana are thermal and hydropower. Although the access rate is relatively high compared to neighbouring countries, Ghana experienced power interruptions leading to load shedding resulting from a deficit in the available capacity against installed capacity. These load-shedding exercises have retarded growth especially in the industrial sector [4, 5]. This is further explained by the 2018 case study in Fig. 3.

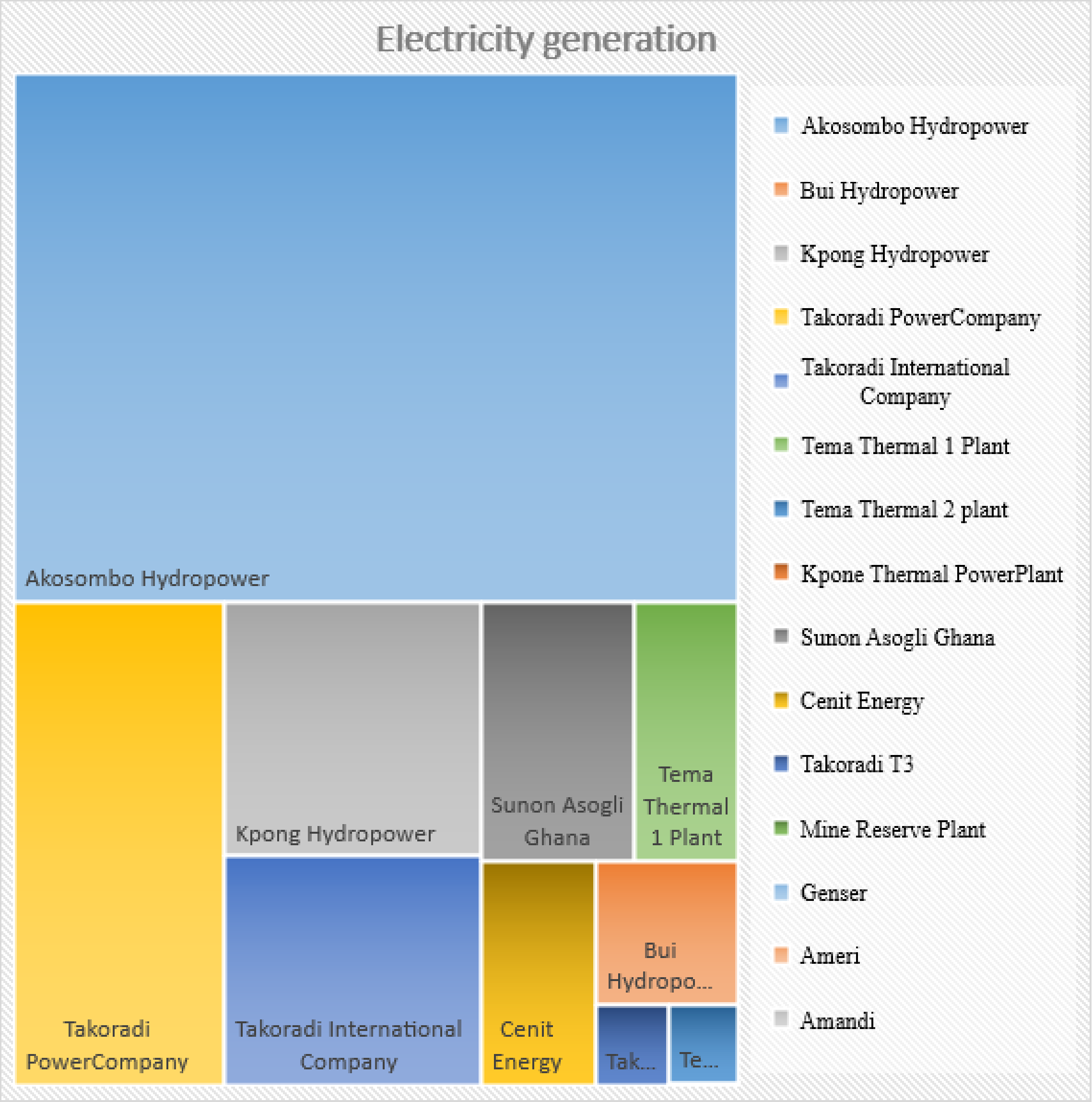


Fig 4 2: Overview of the generation plants in Ghana [6]

Fig 4 3 shows a deficit in available and installed generation capacity. The deficit in hydro generation can be attributed to the effects of climate change – global warming, which has resulted in reduced water volumes flowing into the Volta Lake [7, 8] as well as the damming of the White Volta, one of the tributaries to the Volta lake by neighbouring Burkina Faso, for hydropower purposes. The thermal generation plants are mainly operated as single cycle plants [9], reducing the output as it was designed as a combine cycle. The inconsistent supply of natural gas [10] also affects electricity generation from thermal sources.

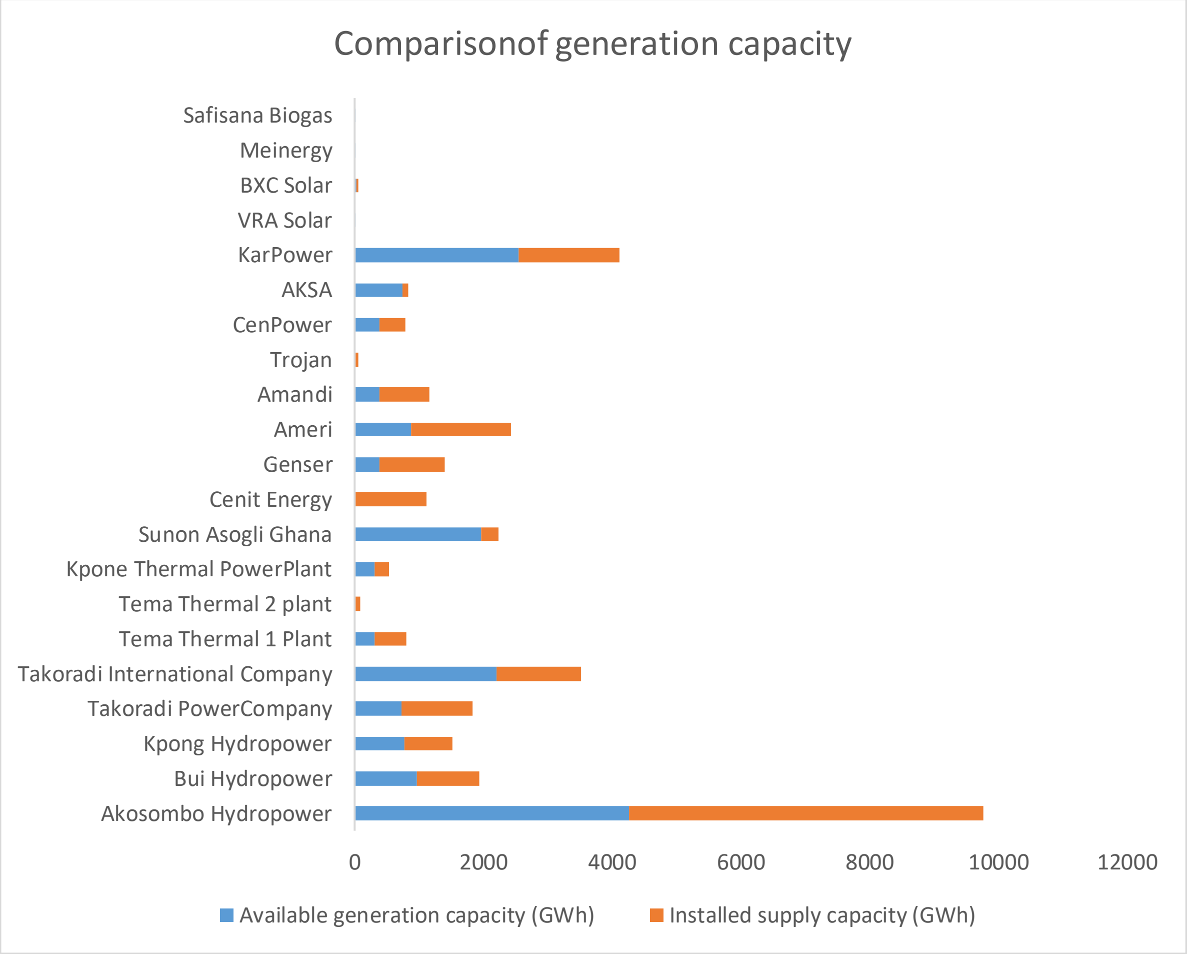


Fig 4 3: Comparison of available to installed generation capacity (11)

Modern renewable energy sources, including mini-hydro, solar, wind, solid biomass, geothermal, and tidal [12], present a reliable alternative to reaching universal access to electricity by 2030 [13], particularly for rural and off-grid communities, and contribute to attaining Sustainable Development Goals (SDG) 7 and 13 simultaneously [14]. The renewable energy potentials in SSA have not been fully explored, according to a study by [15]. However, recent achievements in Ethiopia, with the largest biogas plant in Africa, taking 1,400 tons of bio-degradable materials and waste to produce 80 % of the electricity requirements of Addis Ababa [16] is notable. Southern and northern African countries dominate potential geothermal energy, but Kenya has the highest installed capacity in Africa of 1,037 MW, according to the International Geothermal Association (IGA) [17]. In the most substantial amounts of Global Horizontal Irradiation (GHI) (approximately 10 Km^2, approximately one-third of the continental area). Nationally, there are 12 epicentre countries for GHI, considering at least 50 % superb potential threshold within national limits. 9 of these are located in Africa: Namibia, 96 %, Sudan, 86 %, Niger, 84 %, Egypt, 77 %, Western Sahara, 72 %, Chad, 69 %, Eritrea, 58 %, Libya, 56 %, and Djibouti, 52 %. For DNI, only three countries reach the threshold of the maximum solar potential, with one in Africa –Namibia 77 % [18]. South Africa and Morocco recorded the highest installed capacities of solar power generation plants [19]. Out of the 1,411 MW, medium-to-large-scale identified renewable energy projects in the West African sub-region, about 11.5 % are located in Ghana under the West Africa Power Pool (WAPP) master plan [20].

Ghana has extensive renewable energy policies to encourage renewable energy development [21]. The primary renewable energy sources under these policies include solar, wind, biomass, tidal, landfill gas, geothermal, sewage gas, and mini-hydro (≤10 MW). Only 1.5 % of installed renewable energy capacity was achieved by the target year 2020 [22]. This failure has been attributed to several challenges, including lack of competitive pricing, weak grid infrastructure, limited access to funds, and inconsistent development strategies [22, 21]. The Renewable Energy Master Plan (REMP) was launched in 2019 to address these challenges and provide working guidelines to achieve the country's renewable energy targets. The Renewable Energy Master Plan (REMP) is an extension of the renewable energy Act with a target to reach 10 % renewables in the national electricity generation mix by 2030. The REMP was developed to provide an investment-focused framework for developing and utilising renewable energy in the country [23]. The main goals of the REMP are outlined as follows:

1. Increase installed generation capacity from 42.5 MW in 2018 to 1363.63 MW by 2030
2. Reduce the dependence on biomass as the primary fuel for thermal energy applications;
3. Provide renewable energy-based decentralized electrification options in off-grid communities of 250 MW by 2030.
4. Promote local content and local participation in the renewable energy industry.

The REMP is to be implemented over 13 years, from 2018 to 2030 and would lead to an estimated installed capacity of 2,567 MW in renewable energy plants, 225,000 jobs, and CO_2 savings of about 20.6 million tonnes by 2030 [24]. This study aims to investigate solar energy's potential contribution to achieving universal access to electricity in Ghana by 2030.

4.1.1 Potential of Solar Energy in Ghana

Global electricity demand could be met with available solar energy potential due to its abundant, inexhaustible nature [25–27]. The Global Horizontal Irradiation and Direct Normal Irradiation maps of Ghana in Fig. 4 and 5 show the overall solar potential for thermal and photovoltaic applications. Ghana receives some of the highest amounts of radiation globally, making it suitable for various solar energy applications [28]. Daily solar insolation levels range from 4 kWh/m2 to 6 kWh/m2, with an annual sunshine duration between 1800 to 3000 hours per annum which offers a high potential for solar electricity generation [29]. This data is further confirmed in the Solar Wind Energy Resource Assessment (SWERA) report on Ghana [30].

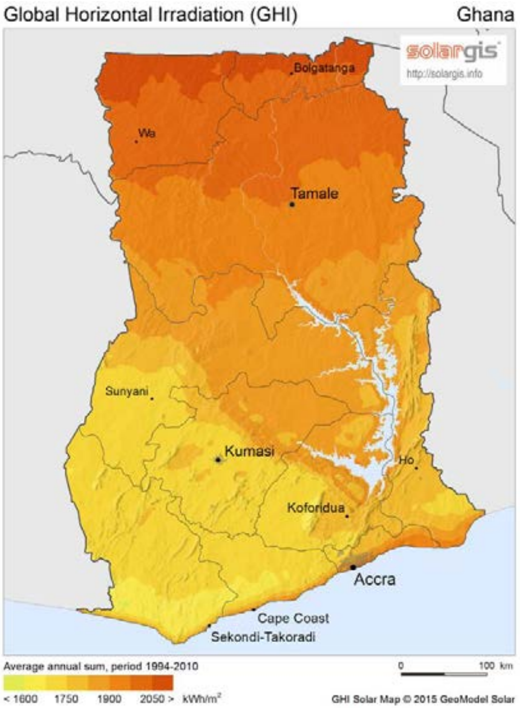


Fig 4 4: GHI solar map of Ghana [31]

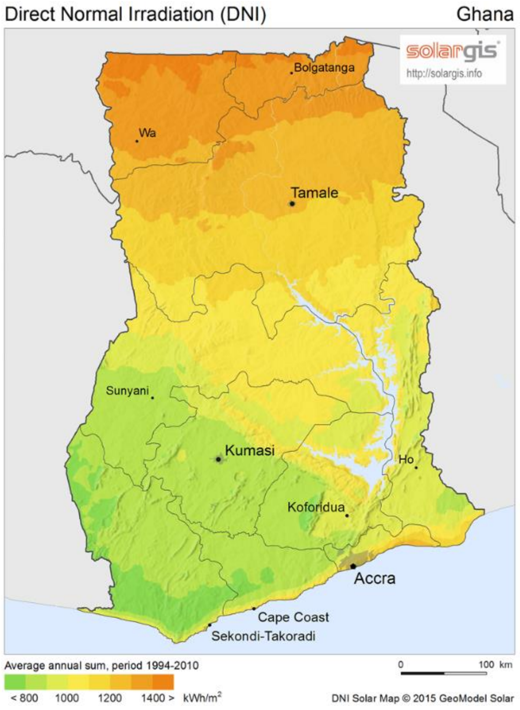


Fig 4 5: DNI solar map of Ghana [31]

Despite this potential, challenges such as political will, technical expertise, components, financing, availability of land, and others have hindered the sector's growth over the years [32]. However, recent research advances have reduced the cost of electricity from solar energy [33]. In Ghana, solar energy installations contribute 90 % of all renewable energy installations, according to a study by Gyamfi [34]. The key issues affecting the implementation of solar energy projects in Ghana in line with the Renewable Energy Global Status Report (2019) standards are presented in Fig. 6. Energy policy is at the heart of the issues affecting the implementation of solar energy in Ghana. Others include solar energy usage for power generation, heating and cooling purposes, technical feasibility, equipment supply, manufacture, and financing.

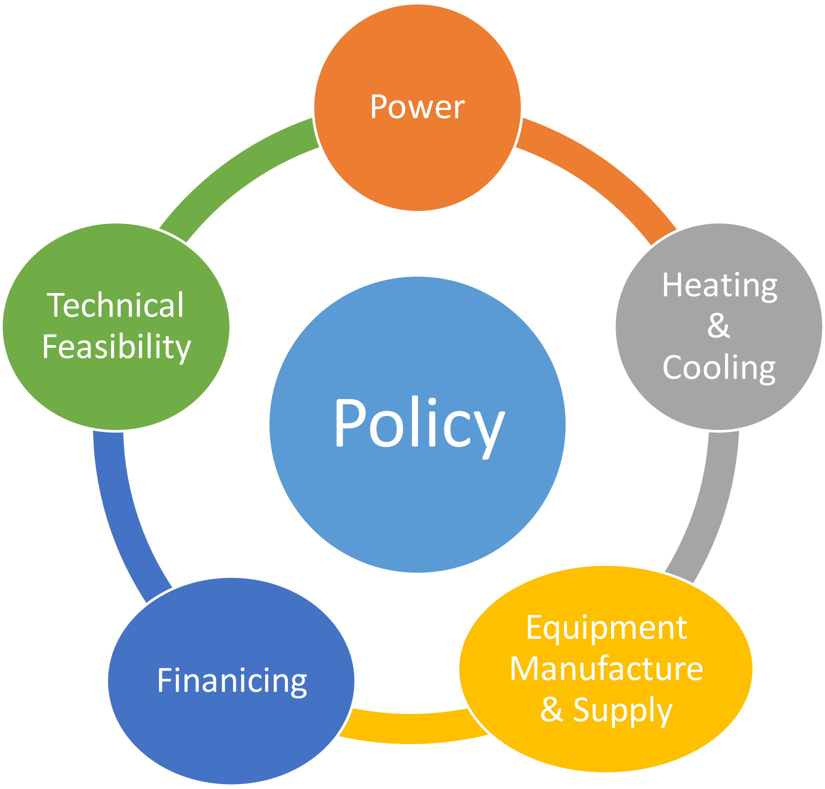


Fig 4 6: Key considerations for solar implementation (35).

4.1.2 Policy

Ghana's Renewable Energy Act (ACT 832, 2011) [36] came into force in 2011 with crucial policy components comparable to global renewable energy policies. The key elements required for policy analysis according to the 21st report of the Renewable Energy Policy Network [37] for renewable policy implementation assessment are power, heating & cooling, technical feasibility, financing, and equipment manufacture & supply. The five key sections are essential to the sustainability of the policy. Table 1 summarizes the comparison of renewable energy policies from randomly selected countries.

Table 4 1: Summary of renewable energy policy from selected countries

Country	**Principal support (fit/rps)**	**Investment support/ subsidies**	**Financing/ public loan**	**Target**	**R&D**	**Highlights**
USA	RPS	Yes	Yes	25 %, 2025	Yes	Investment and production tax credit [38]
Canada	FIT	Yes	Yes	90 %, 2030	Yes	Production incentive of 1 CAN cent/kWh for the first ten years [39]
Germany	FIT	Yes	Yes	65 %, 2030	Yes	Electricity feed-In-Tariff, emission trading subsidies [40]
Spain	FIT	Yes	Yes	42 %, 2030		subsidies [41]
France	FIT	Yes	Yes	27 %, 2020		Subsidies [42–44]
China	FIT	Yes	Yes	30 GW, 2020 Yes		Locally made components, investment, emission trading [45, 46)]
Pakistan		Yes	Yes	30 %, 2030		Solar thermal [47]

In 1989 the National Electrification Scheme (NES) was passed within a 30-year timeframe (1990-2020). The objective of NES was to improve electricity access in the country, especially in rural areas with more than 500 people [48]. Later, this was expanded to include the Solar National Electrification Scheme (SNES). According to Steel et al. [49], SNES employed the fee-for-service approach. This approach was very encouraging as the use of photovoltaic systems in off-grid rural areas.

The National Energy Policy (NEP), which preceded the Renewable Energy Act in 2010, targeted adding 10 % of renewable energy generation sources to the national generation mix by 2020 but has since been extended to 2030 under the REMP scale-up program. The main highlights of the NEP implementation include off-grid electrification systems, power purchase agreements, net metering systems, and licensing schemes. Additionally, the government offers a straightforward performance of tax incentives and importation fee exemptions for some renewable energy components [50].

Measures such as grid code for utility-scale renewable energy grid interconnection; net metering code; a standard Power Purchase Agreement (PPA); guidelines on renewable energy purchase obligation; a detailed and concise licensing framework; and an attractive feed-in tariff were put in place to implement the NEP. Solar photovoltaic (PV) has a guaranteed rate of GHC 0.60/kWh (US$ 0.11) for the first ten years. The Sustainable Energy for All (SE4ALL) [51], developed in 2012, also seeks to address the provision of off-grid renewable energy-based solutions, thereby complementing ACT 832. Under SE4ALL, national electrification coverage increased from 66.7 % 2008 to 76 % in January 2015 [52] and 82.5 % in 2019. As one of its objectives, the SE4ALL targets deploying an additional 50,000 Solar Home Systems (SHS) to add up to the existing 71,600. The private sector companies also aim to deploy additional 120,000 SHS by 2030. The SHS is categorized under T1 (≤30 W), T2 (30 W - 150 W), and T3 (≥150 W) [53].

In line with the Intended Nationally Determined Contributions (INDCs) [54], Ghana intends to generate compliance grade emission reduction units from actions in the waste and energy sectors. The Reducing Emissions from Deforestation and forest Degradation (REDD+) program [55] enlisted on the World Bank’s Forest Carbon Partnership Facility (FCPF) REDD+ Readiness Programme also targets forest carbon emission reduction from 2012 to 2032. The Readiness Plan Idea Note (R-PIN) was expanded and approved in 2010 for the REDD+ program [56].

All these policy interventions, coupled with average solar insolation of 4 kWh/m2/day – 6 kWh/m2/day according to a study by Matuska et. al. [57], have aided in putting solar energy at the forefront of renewable energy deployment in Ghana.

4.1.3 Solar Heating and cooling

Solar heating and cooling utilize solar thermal energy to provide heating and cooling for applications such as water heating [58, 59], industrial process heating [60, 61], and cooling [62, 63], to name but a few. In Ghana, solar cooling is almost non-existent compared to solar heating [64]. Solar heating is applied mainly to water heating and crop drying. The hospitality and food processing industries primarily use solar water heaters (SWH). Flat plate and evacuated tube collectors are the commonly used thermal collectors in Ghana. Characteristics such as insulation and glazing affect efficiency considerably [65]. The main challenges that have been encountered in the mass adoption and usage of solar water heaters are the high cost of maintenance because of the high level of chlorine in the copper pipes, low water pressure, and irregular supply from the source (Ghana Water Company), which often renders many installed systems non-functional as in a study by Dao et al. [66]. Damage through sand is rampant in the arid regions, especially in northern Ghana.

4.1.4 Solar power

Solar power mainly refers to solar energy for electricity generation and lighting purposes [67, 68]. In Ghana, solar electrification is one of the critical applications championing solar energy implementation [69]. Efforts in the sector are summarized in table 2.

Table 4 2: Summarized solar power projects in Ghana.

Project	Applications	Year
SNES [70)]	Electricity	1990
Eleanor project [71].	Electricity	2014
Association of Ghana Solar Industries [72)]	Electricity/lighting	2006
Gesellschaft für Internationale Zusammenarbeit (GIZ) [73]	Solar Community kiosk	2014
Government – private partnership [74]	Electricity/lighting 2012	
Volta River Authority [75]	Electricity	2015
Private investors	Electricity / lighting	2013

There has been progressive growth in installed solar energy capacity since 2013 (mainly from solar photovoltaics), as shown in Table 3. Solar thermal sources have not contributed significantly to solar energy growth due to several factors but primarily the lack of political will, as in a study by [76] in Nigeria. Unfortunately, the cost of solar thermal technology has not declined as in the case of solar photovoltaic systems, which also discourages investment in the sector [77]. Electricity generation from solar energy has increased due to the policy interventions and concise implementation strategies mentioned in section 2.1. The implementation of Act 832 (the Renewable Energy Act) has further aided the growth of the solar energy sector, although the growth rate is below the target.

Table 4 3: Summary of solar power growth effectiveness in Ghana.

Year	**Installed capacity (MW)**	**Operational capacity (GW)**	**Consumption capacity (GWh)**	**Generation capacity (GWh)**	**% Share in the national energy mix**
2013	2	2	5.26	5.26	0.07
2014	2.5	2	4	4	0.05
2015	2.5	0.5	4	4	0.04
2016	22.5	11.5	28	28	0.2
2017	51	-	-	-	1
2018	70	-	-	-	1.4

4.1.5 Equipment supply and manufacture industry

To promote solar technology in Ghana, Strategic Security Systems (3SiL) began the solar PV module assembly in Ghana in 2015 with a production capacity of 30 MW modules per year. Other companies include Halo International 2016, with a production capacity of 15 MW per year, and Atlas Business and Energy Systems (ABES). Africano Electro Ltd, Power Wings Company Ltd, Panasonic, and Deng Ghana Ltd, among others, are setting up manufacturing /assembly plants for renewable energy components. Trade works Ghana Ltd., with a 12 MW per year capacity, is yet to commence operations.

4.1.6 Technical feasibility

Several studies by Quansah et al. have been conducted in Ghana on solar photovoltaics. The studies show that most modules in Ghana meet and exceed warranty expectations of up to 10 years at 90 % capacity and 25 years at 80 % capacity, meeting the international standards on technical feasibility [78]. Furthermore, polycrystalline (pc-Si) solar cells have been found to be more economical [79, 80]. Heterojunction Incorporating Thin (HIT) films were comparatively more energy-efficient [81]. Another study on solar photovoltaics in Africa [82] recommended the transition from solar home systems to grid-connected or mini-grids to achieve the 2030 target of universal access to electricity for all under the SE4All project. In distributed and decentralized systems, stronger regulations need to be developed. Africa also needs to integrate significant shares of large-scale centralized power plants. However, the choice of a photovoltaic panel depends on a number of factors such as the availability of land and the cost of the panel and storage [83, 84] in line with the global characteristics. Systems with tracking are, however, unpopular. Ghana, therefore, has the technical capacity to increase its installed capacity.

4.1.7 Financing

Globally, Investment in renewable energy continued to focus on solar power, particularly solar PV, which increased its lead over wind power in 2017 [85]. Small-scale solar PV installations (less than 1 MW) had an investment increase of 15 %, to USD 49.4 billion. Developing and emerging economies overtook developed countries in renewable energy investment for the first time in 2015 and extended their lead in 2017, accounting for a record 63 % of the global total, due mainly to China [86]. Investment in developing and emerging countries increased by 20 % to USD 177 billion, while developed countries fell 19 % to USD 103 billion [87]. China accounted for a record 45 % of global investment in renewables (excluding hydropower larger than 50 MW), up from 35 % in 2016, followed by Europe (15 %), the United States (14 %), and Asia-Oceania (excluding China and India; 11 %) [69, 88]. Smaller shares were seen in the Americas (excluding Brazil and the United States, 5 %), India (4 %), the Middle East and Africa (4 %), and Brazil (2 %) [71]. Ghana accessed a US$2 billion concessional Line of Credit for Renewable Energy following Parliament's ratification of the country's membership in the International Solar Alliance (ISA) [89]. The Green Climate Fund (GCF), 2017, has also released funds to support Renewable energy projects. Internally generated funds from the IRENA – ADF project facility, ECREEE, and the private sector will decrease the entire financial burden on consumers/project funders [90]. The Renewable Energy Master Plan (REMP) is a US$ 8 billion investment master plan. On an annual basis, the REMP translates into an estimated US$ 620 million in investments [91]. The development of the domestic financial sector to accept and manage credits for renewable energy installations at domestic, commercial, and industrial levels must be further developed in Ghana.

4.2 Methodology

This paper employs the Low Emissions Analysis Platform (LEAP) to model solar energy development in line with the REMP towards attaining universal access to electricity by 2030. LEAP was also used to model scenarios of energy as well as the CO_2 emission reductions in the respective scenarios up to 2030, similar to the study by [92]. A model was developed in the Low Emissions Analysis Platform (LEAP) to forecast energy demand using historical data. Data on electricity demand was divided into four subsectors, namely, residential, non-residential, special load tariff (SLT), and street lighting sectors. Existing energy generation plants were included in the model to study the energy demand and supply dynamics. Greenhouse gas (GHG) associated with energy generation is estimated in the model. A reference scenario was developed using existing demand and supply data. Other scenarios were created from the reference scenario to depict the various solar penetration levels in the energy supply plan. The methodology consists of optimistic projection scenarios similar to studies by Emodi et al. [93] for Nigeria and Nieves et al. [94] for Columbia.

4.2.1 Low Emissions Analysis Platform (LEAP)

LEAP is a software tool for energy policy, climate change mitigation, and air pollution decline forecasting. It is an integrated modeling tool that can track energy consumption, production, and resource extraction in all sectors of an economy. It can account for both the energy and non-energy sectors of greenhouse gas (GHG) emission sources and sinks, in addition to tracking GHG. LEAP is designed around the concept of long-range scenario analysis. Scenarios are self-consistent storylines of how an energy system might evolve.

LEAP is not a model for any specific energy system but a tool that can be used to generate models of diverse energy systems, where each needs its own unique data sets. LEAP supports various modelling methodologies: on the demand side, these range from ascending, end-use accounting techniques to descending macroeconomic modelling. On the supply side, LEAP runs a range of accounting, simulation, and optimization methodologies for modelling electric sector generation and capacity expansion planning, but also malleable and easy to allow LEAP to incorporate data and results from other more specialized models. This study focused on data from the demand and supply sides.

LEAP’s modelling capabilities operate at two basic conceptual levels. In one methodology, LEAP's built-in calculations handle all energy, emissions, and cost-benefit accounting calculations. On the other hand, users enter spreadsheet-like expressions that can specify time-varying data or generate a wide variety of sophisticated multi-variable models, thus enabling econometric and simulation approaches to be embedded within LEAP’s overall accounting and optimization frameworks. This paper utilized the built-in calculations method.

4.2.2 Model parameters

The base year used for the model was 2013 because that was the year the renewable energy Act (ACT 832) was enforced. The end year for the model was 2030, in line with the target year specified in the Renewable Energy Master Plan (REMP) and the target for Act 832. In modelling energy demand and supply in LEAP, historical data from 2013 to 2018 (from the Ghana Energy Commission) was used to project demand and supply from 2019 to 2030.

4.2.3 Demand and Supply Projections

Energy demand data was grouped under residential, non-residential, special load tariff (SLT), and street lighting sectors. The average year-on-year growth rate used in the demand projections was calculated using historical data from the Ghana Energy Commission between 2000 and 2018. The demand projections were made along the lines of the existing energy demand sectors. On the supply side, as of 2018, existing generation facilities were modelled in LEAP. These together were developed into the reference scenario subsequently referred to as the Business-As-Usual (BAU) Scenario from which the Solar Transition scenarios were developed.

4.2.4 Solar Transition Scenarios

Based on the Business-As-Usual (BAU) supply scenario, the Low Transition (LT) Supply Scenario, Moderate Transition (MT) Supply Scenario, and Visionary Transition (VT) Supply Scenario was developed to reflect the various levels of solar energy penetration in the generation mix. In the BAU, the actual installed generation capacity available as of the end of 2018 was deployed in the scenario to meet the electricity demand till 2023. The solar transition supply scenarios added 5 %, 10 %, and 15 % of installed solar energy generation systems in the LT, MT, and VT, respectively.

4.3 Results and discussion

The scenarios investigated and analyzed were the Electricity demand scenario, electricity supply scenario, BAU scenario, LT scenario, MT scenario, VT scenario, carbon dioxide (CO_2) emission scenario, and a comparison of carbon dioxide emission reduction scenario.

4.3.1 Electricity demand scenario

The electricity demand projections are based on all fuels in the business-as-usual scenario shown in Fig.7. The total demand growth rate is 8 % per annum, 2 % lower than the GDP growth rate projection of the Ghana grid company (GRIDCo) (95). The tolerance given in the GRIDCo projections for other demand sectors is accounted for this. In contrast, this study is based on available data for the four primary demand sectors from the Energy Commission. The residential and street lighting growth rate is expected to be 8 %, whilst non-residential and particular load sectors increase by 9 % per annum. The dips in the demand growth curves resulted from the load shedding exercises. The load shedding exercise resulted from supply being unable to meet demand. A schedule was created to cut supply at certain times to create a balance. Most often, though, these power cuts were random. Most industries resulted in independent power plants continuing production for the safety of their equipment, according to (96). This shifted the demand for electricity from the national grid to private diesel generators.

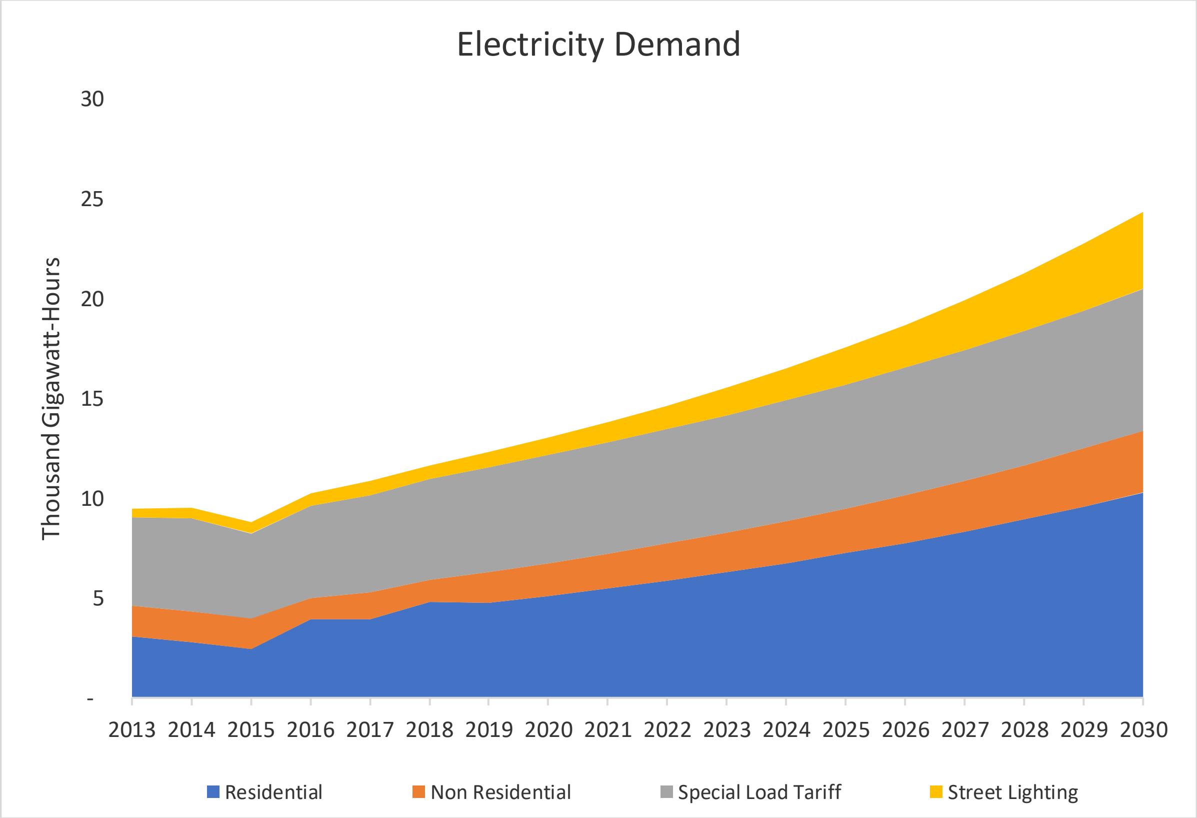


Fig 4 7: Electricity demand in Ghana.

4.3.2 Supply Business-As-Usual (BAU) Scenario

Electricity generation capacity in the business scenario is more than 1,000 GWh, as shown in Fig. 8. This indicates that Ghana has more than enough installed generation capacity to meet demand. Therefore, Ghana's inability to meet demand challenges finances by prioritizing crude oil purchasing. A study from [97] argues that monetary policy has lessened the negative growth consequences of oil price shocks at the cost of higher inflation. Therefore, policymakers are torn between higher inflation or negative growth. From 2016, generation capacity increased substantially with an increase in generation from Tema thermal plant 2, Trojan, Kar power, and BXC solar. Except for BXC solar, all plants mentioned above required crude oil for generation. Kar power started generation in 2015 but increased from 64 GWh to 1,822 GWh by 2016. However, the Takoradi T3 and my reserve plants were decommissioned in 2016 and 2017, respectively. The AKSA plant started generation in 2017, as shown in Fig. 8. Genser, Meinergy and Safisana Biogas plants also started generation in 2018. 34.6 % of generation capacity would come from the Akosombo, Bui Hydro, and Kpone power plants, with thermal production accounting for 66.8 % of projected national generation by 2030. However, solar energy should contribute 12.4 % of generation by 2030 in the BAU scenario.

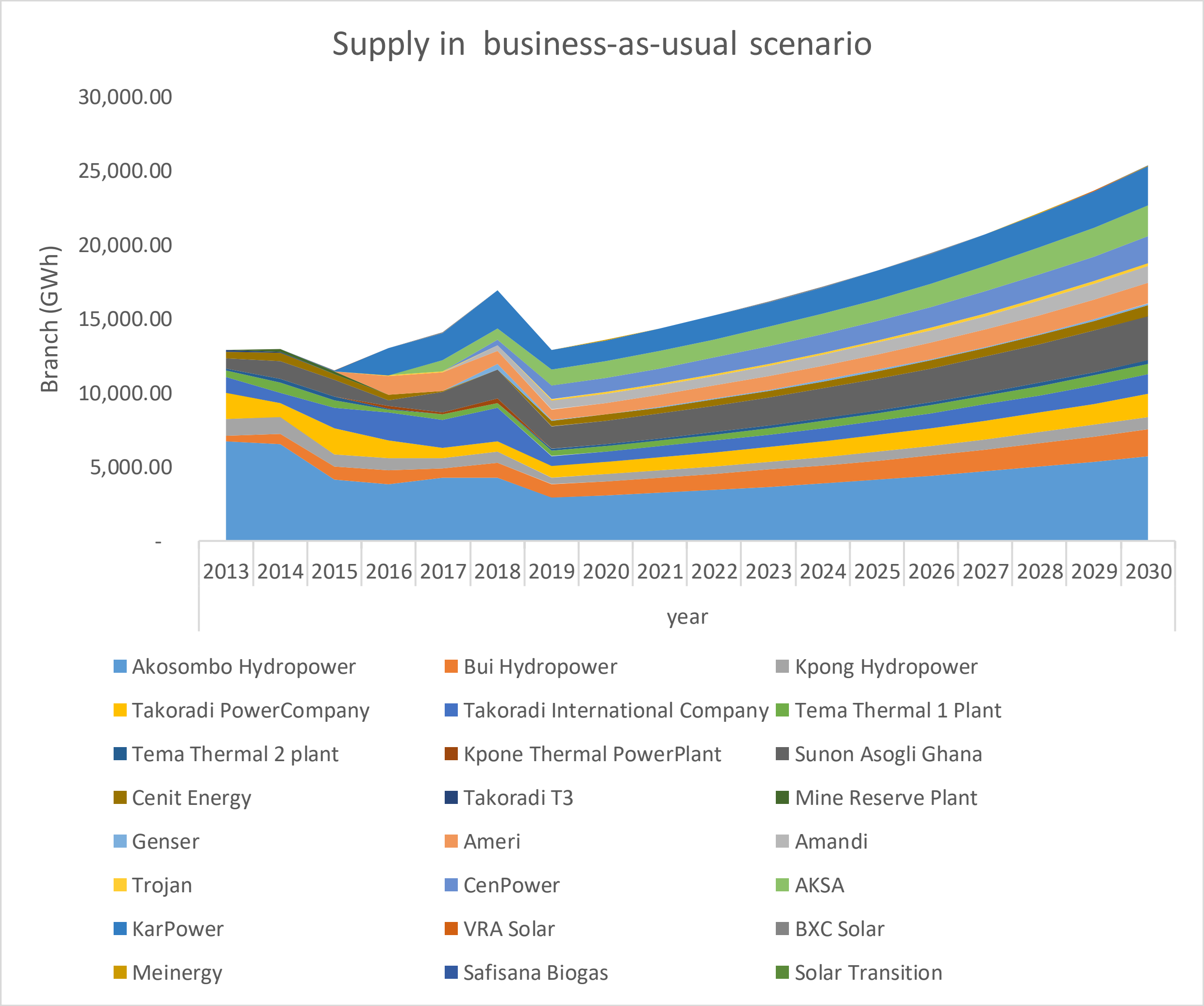


Fig 4 8: Electricity supply in the Business as Usual (BAU) scenario

4.3.3 Solar transition scenarios

This chapter aims to explain the three main scenarios considered; Low, moderate, and visionary transition scenarios. In the low transition scenario, the total solar installed generation was

projected to increase by 5 %, as shown in Fig. 9. Therefore, the generation rises from 70 MW in 2020 to 270 MW in 2030. The residential and non-residential sectors contribute 42 % and 13 % (highest and lowest) demand sectors in 2030. Solar generation could contribute 2.6 % of residential demand or 8.7 % to non-residential demand in 2030. Averagely, 2.3 % of total demand could be met in the low transition scenario, leaving a deficit of 1093.63 MW by 2030 of the 1363.63 MW target of REMP.
In the moderate transition scenario, shown in Fig.10, the solar transition was projected to increase by 10 %, in line with the target in the renewable energy Act. The solar installed generation could contribute 5.2 % of residential demand or 17.1 % to non-residential demand in 2030. This could also contribute to 482.46 thousand GW of solar energy in 2030.

For the visionary scenario shown in Fig. 11, the solar transition was projected to increase by 15 %. Solar generation could contribute 8.1 % of residential demand or 26.8 % to non-residential demand in 2030. Approximately 784.13 thousand GW of solar energy could be contributed by 2030. As island communities are the main targets of solar off-grid systems, the visionary scenario could help Ghana attain a 100% electrification rate by 2030.

According to a study by [98], South Asia's success story could be emulated. Strategies include mobilizing funds domestically (e.g. bonds, shares, etc.). Investments include the provision of government on-lending facilities/loans to solar projects. Competitive procurement could be institutionalized to achieve price reduction in solar tariffs. Initiatives such as upgrading the National Interconnected Transmission System [99] (system control centre, weather forecasting systems, etc.); driving developments onto lands that do not compete with other uses (e.g. abandoned mineral mine sites) and encouraging the contribution of land as equity in solar projects should be encouraged.

The government can also continue providing incentives through the energy levy and intensify awareness creation and capacity development for stakeholders.

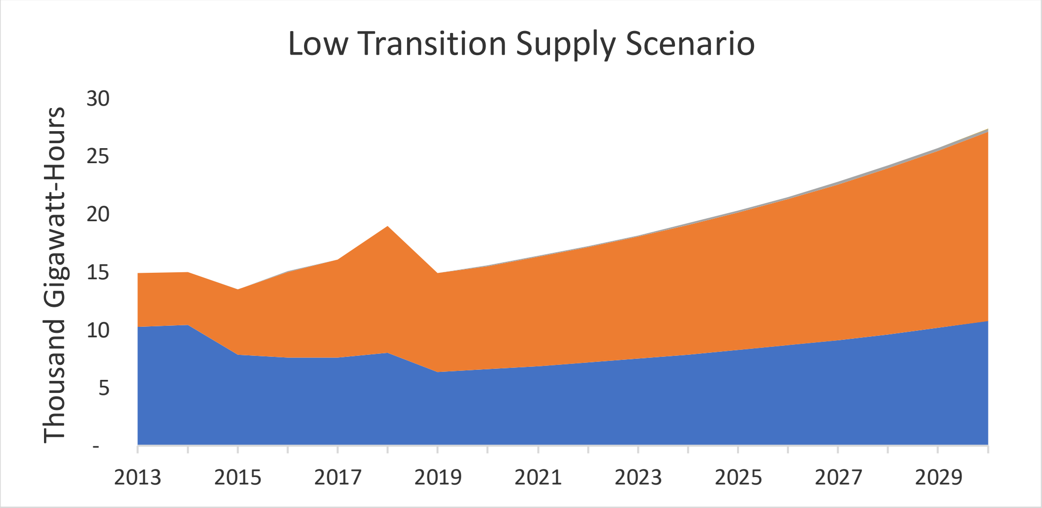


Fig 4 9: Electricity supply in the Low transition scenario.

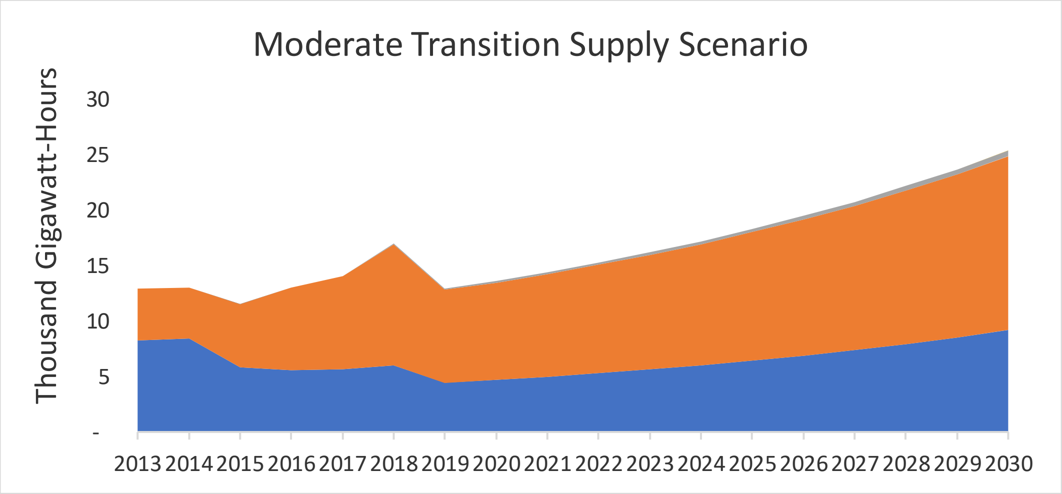


Fig 4 10: Electricity supply in the Moderate transition scenario.

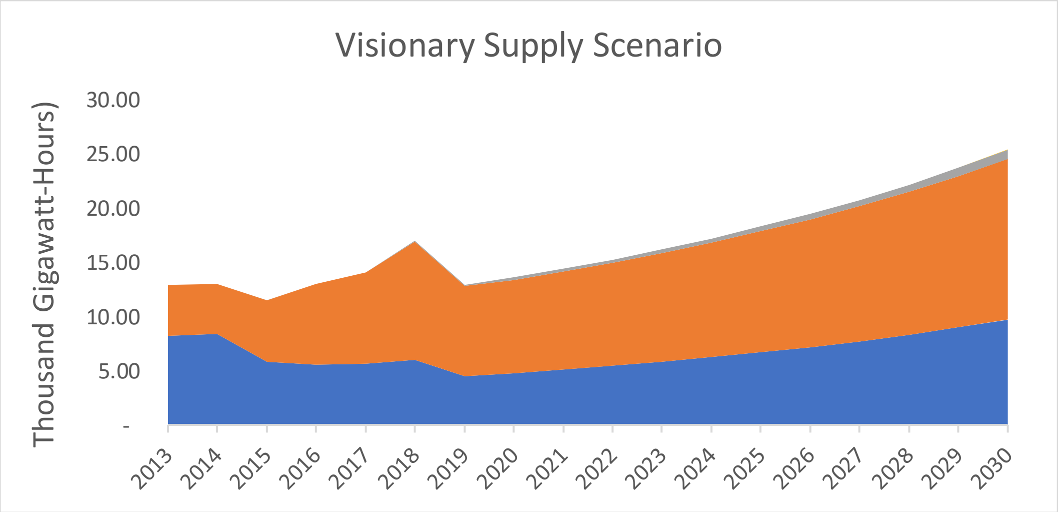


Fig 4 11: Electricity supply in the Visionary supply scenario.

4.3.4 Carbon emissions

Generation emissions were the same until the introduction of the solar transition scenarios, as seen in Fig.12 below. The maximum emissions occurred in the Business-As-Usual (BAU) supply scenario. However, the minor emission was from the visionary supply scenario, although the maximum solar generation was from this scenario. The BAU supply scenario emits 80.8 % more carbon dioxides than the visionary scenario. Increasing solar energy will therefore reduce the carbon emissions from electricity generation significantly. The moderate and low supply scenarios follow, respectively.

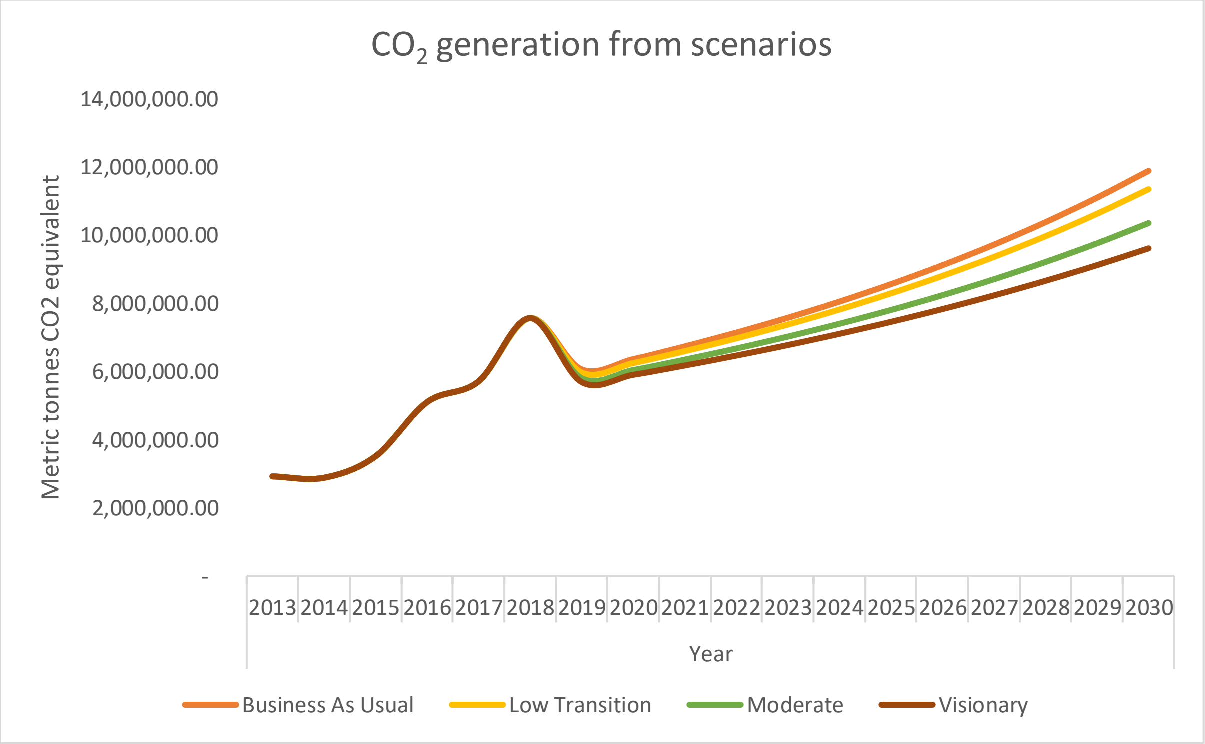


Fig 4 12: Carbon dioxide generation from the various scenarios.

4.3.5 Avoided carbon emissions

Fig.13 shows the avoided carbon emissions in the BAU, low, moderate, and visionary scenarios compared to fossil power production sources. This shows that the highest amount of emission avoided would be in the visionary supply scenario if this effort coupled with similar avoided emissions from biogenetic emissions from power generation would reduce drastically, according to a study by [92]. By 2030, 3.31 million metric tonnes, 9.33 million metric tonnes, and

13.66 million of CO2 would be avoided in the Business-as-usual, low, moderate, and visionary scenarios. This would help the country reduce its carbon emissions as part of its efforts to reduce global warming in line with the Intergovernmental Panel on Climate Change (IPCC) protocols [100].

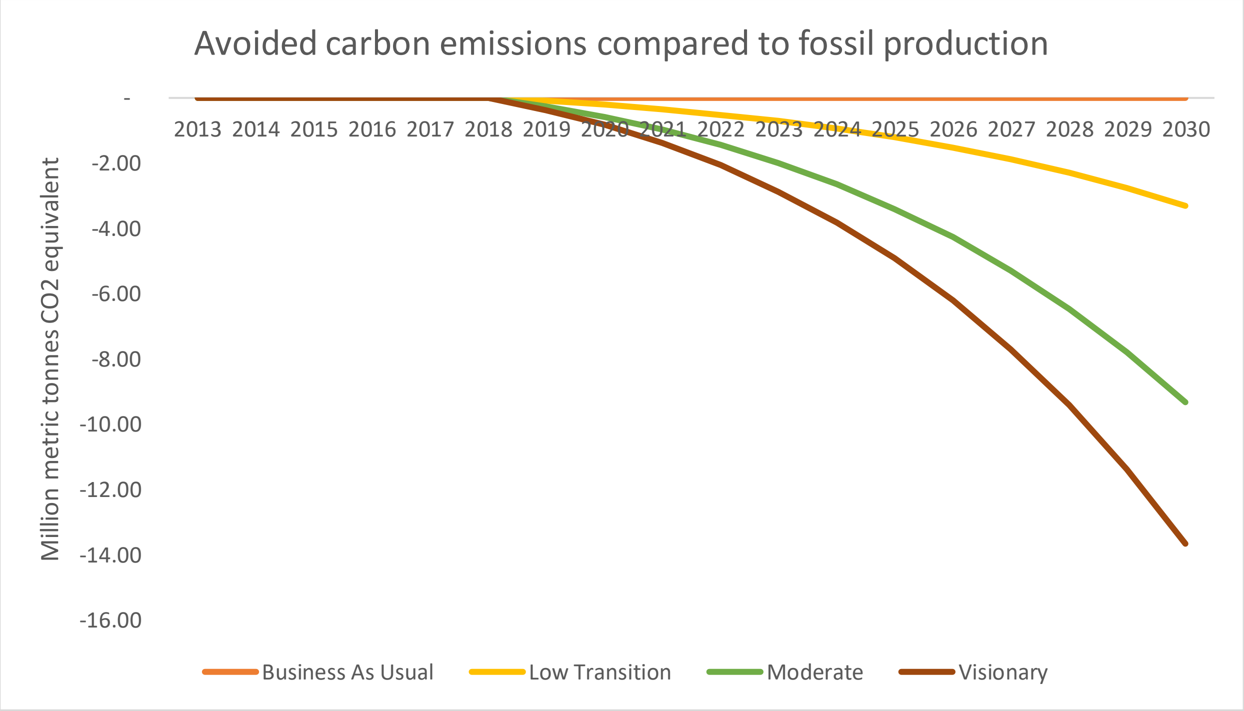


Fig 4 13: Avoided carbon emission compared to fossil production

4.4 Conclusion and policy implications

Three main solar energy transition scenarios were designed, including demand projections and supply; the demand projections indicated that residential demand is projected to increase substantially, followed by special load tariff, non-residential, and street lighting, respectively. The residential growth, however, experienced a sharper growth rate in comparison to the other three sectors. Solar energy for the residential sector is therefore recommended to help meet demand.

Four main supply scenarios were designed using LEAP. The business-as-usual supply scenario was designed based on the current supply rate, which cannot meet the target set in the renewable energy master plan. The low transition, moderate and visionary scenarios increased solar transition by 5 %, 10 %, and 15 %, respectively. Appreciable gains were made in the low and moderate transition scenarios. However, the visionary supply scenario can meet the renewable energy target by 2030 with solar energy. Implementation strategies include tax incentives, solar subsidies, promotion of local manufacture of solar systems, prioritizing solar thermal power generation, and crop drying. Also, strengthening the national grid to encourage grid interconnection, net metering incentives, and investment in the solar generation sector is recommended.

In line with environmental concerns with power generation, power generation from solar energy reduces carbon emissions compared to thermal power generation. Most importantly, the visionary supply emission scenario produces 80.8 % fewer carbon emissions whiles generating 15% more solar power. In Comparison to the Business-as-usual supply scenario with the visionary scenario, over 13 million metric tonnes of CO_2 will be offset by 2030. This will help the country keep global temperature increase below 2°C – Sustainable Development Goal 13. Sustainable Development Goal 7 – clean energy targets could also be implemented by promoting solar energy. As Ghana prioritized energy in its Intentionally nationally determined contributions (INDCs) with a target of 100 % electricity access by 2030, an increase in solar energy generation can also aid in the earlier achievement of this target. The framing of solar energy deployment as a strategy for sustainable economic growth is strongly recommended.

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5 A FRAMEWORK FOR OPTIMIZATION OF ENERGY EFFICIENCY AND INTEGRATION OF HYBRIDIZED-SOLAR ENERGY IN AGRO-INDUSTRIAL PLANTS: BIOETHANOL PRODUCTION FROM CASSAVA IN GHANA.

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Abstract

This study presents a methodological framework for auditing, optimization, and integration of hybridized solar energy in Ghana's agro-industrial sector. The Functional Analysis System Technique is introduced for systematically translating plant-wide energy requirements into detailed functional and performance design criteria for energy efficiency, optimization, and solar energy integration. The results of the case study indicate that insulating the fermenter and distiller and using energy-efficient rasper, pumps, and cables reduce overall energy consumption by 41.8%. A 250 kW solar photovoltaic model is designed with a performance ratio of 75% and a thermal fraction of 91% for the solar hot water system. The cost of integrating solar thermal energy is 31.8% higher than solar photovoltaic power due to the lack of subsidies in the sector. The framework, therefore, presents an invaluable tool for optimizing energy efficiency and integrating solar thermal and solar photovoltaic for the agro-industry sector.

Keywords: Framework, optimization, solar energy integration

5.1 Introduction

The agriculture sector contributes 6.4% of the entire world's economic production, led by China (19.49 %) and India (7.39%) [1, 2]. Ghana's economy has grown substantially over the past decade, with agriculture accounting for 50 % of the total employment [3] and 25 % of the country's Gross Domestic Product [4, 5]. However, the estimated agricultural growth of 8 % per annum has reduced to 3.3 % [6] per annum. The costly and unreliable electric power supply is one of the critical constraints hampering more significant economic growth in

Ghana's agricultural sector[7]. Although Ghana has an electrification rate of 82.5%, installed capacity far outweighs generated capacity [8].

Further worsening this challenge is that agro-processing plants are commonly sited close to farms and not in the designated industrial hubs. This was realized in the field study where 23 agro-processing plants were visited nationwide. It was observed that 83% of the agro-processing plants were sited close to farms where they obtain their raw material (not in industrial hubs close to electricity from the national grid). Also, most agro-processers relied on an independent power supply [9].

As a possible source of relief to the overwhelmed national grid, Ghana's renewable energy ACT (ACT 832) states that 10% of the total energy should come from renewables by 2020, and solar energy forms 90% [10] of renewable energy in the national mix. Despite the abundance of solar energy resources in the country and active legislation supporting the utilization of solar energy as an alternative energy source, active usage to supplement the energy needs in industrial-scale agro-processing is still scarce. Even though a significant amount of research has been presented in the literature looking at different aspects of Ghana's solar energy sector, what we know is mainly focused on assessing the availability of solar energy resources while prioritizing residential energy efficiency over the industrial or commercial sectors [11–13]. Some studies have drawn on an extensive assessment of solar photovoltaics for resistance heating, focusing on self-consumption [14–16]. While others have illustrated that when installed photovoltaic investments reduce below 2 €/Wp, it may become the lower-cost heating option relative to solar thermal [17, 18]. However, it is essential to mention that even though this investment threshold is already prevalent in many markets [19], there is minimal information for the case of Ghana. A broader perspective comparing solar and bioenergy systems has been adopted [20, 21], and the results argue bioenergy is predicted to contribute more than solar thermal energy by 2050 [22, 23]. However, this study required a maximum temperature of 107°C, making solar thermal energy integration [24–28] a more energy-efficient option for generating process heat [26, 29–32].

Although there are several studies on energy efficiency [33–36] and solar process heat integration [37–40], among others, have been conducted. Also, tools such as GREEN FOODS tool, Pinch analysis for energy efficiency in chemical process, Aspen Hysys for chemical process simulation, Attainable regions for process analysis, RETscreen, and TRNSYS (Transient system simulation) for renewable system design [41–46]. However, Ghana has not adopted any framework for hybridized solar energy integration in the industrial sector, especially the agro-industry [47]. The main challenge now lies in establishing a robust and accurate framework for optimally analyzing energy requirements and integrating existing forms of solar energy to supplement agro-industry energy demands. Such a framework will be a breakthrough in supporting the transition towards a more sustainable solar-powered industry in Ghana. Therefore, this paper is designed to provide and evaluate the performance of a conceptual framework for simultaneous optimization of energy efficiency and integration of hybrid solar energy in agro-industry sector plants. This study will provide sustainable energy for the agro-industry and reduce demand on the national grid. Fig 5 1 presents the conceptual framework that models the activities necessary for optimizing energy efficiency and integrating hybridized solar energy in the agro-industry sector. The framework consists of seven key modules, which include:

(1) The goal-setting module defines the energy objectives for the plant.
(2) The industrial plant module describes the activities conducted at the process plant's level.
(3) The information module outlines the regulatory data obtained from other sources.
(4) The energy efficiency module, which illustrates activities, is involved in auditing and optimising the plant's energy efficiency.
(5) The energy integration module,
(6) data modelling, and analysis module involve computations performed on the data collected.
(7) The data interpretation module translates the theoretical results into plantwide recommendations.

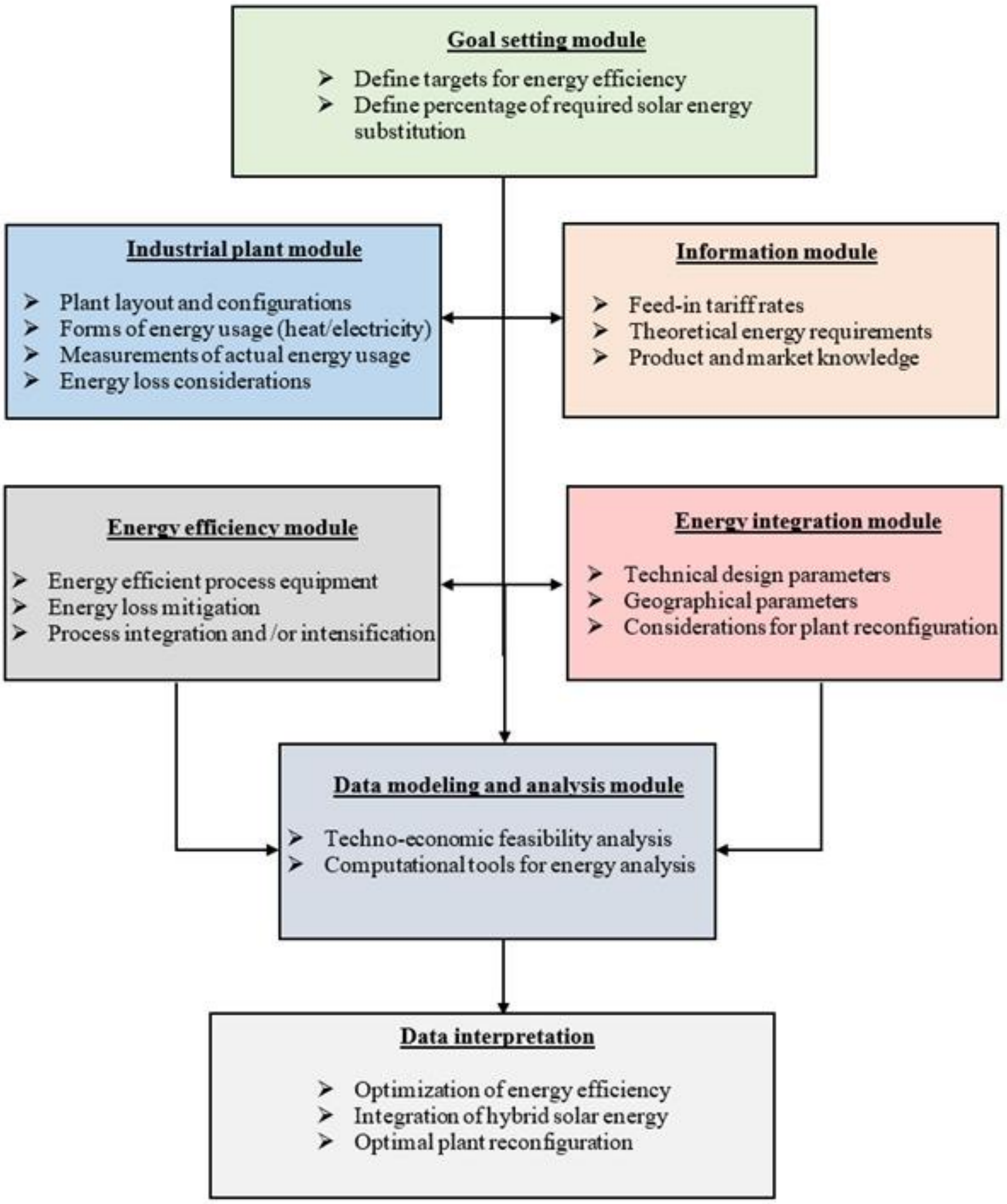

Fig 5 1: Conceptual framework for simultaneous optimization of energy efficiency and integrating hybrid solar energy in industrial plants.

The research methods included a site visit for an initial assessment followed by a detailed energy audit over a 28-day period. The energy audit first categorises the plant operation into four (root preparation unit, mashing/liquefaction unit, fermentation unit, distillation unit) central units shown in Fig 2 below. The energy required for each unit operation was measured and recorded. The mass and temperature of the unit processes were also recorded. This was then compared to the designed or theoretical values obtained from the plant manager. The system was then optimized. The optimized results served as the data for a hybridized solar energy system design using the System Advisor Model. The design was validated for its technical and economic efficiency relative to traditional electricity from the national grid.

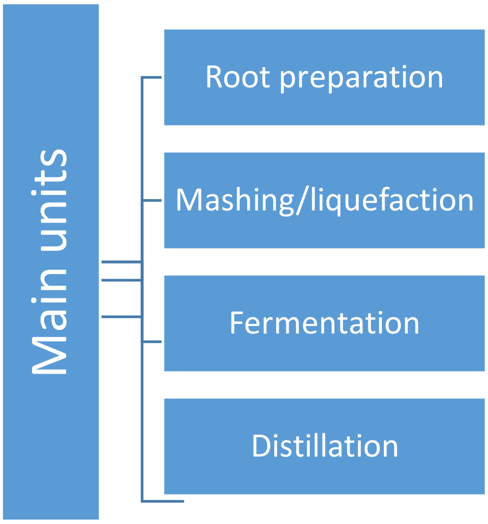

Fig 5 2: The energy audit considers four central units in the bioethanol production process.

5.1.1 Case description: Ethanol production from cassava

In Ghana, the National Agricultural Research Systems (NARS) has released over 24 improved varieties, whiles the Council for Scientific and Industrial Research (CSIR) has released 11 varieties [48–50] for commercial cassava farming. Due to the low ash content and rich organic nature, it can be used as an ideal substrate for bioethanol production [51].

Fig 5 3: Cassava root crop

Ghana has two primary industrial cassava processing plants in the Volta and Central regions of Ghana, respectively. The research focus is a bioethanol plant that produces ethanol and liquefied CO_2 from cassava at Hodzo, in the Volta region of Ghana. The plant depends on a 500 KVA diesel-powered generator due to unplanned load shedding exercises on electricity from the national grid [52]. The hot water supply is from a steam boiler on site. The generator emits 2398kg of carbon dioxide per 900 kg of deiseal consumed. Fuelwood is the energy used in the steam boiler 548.64 kg/h at 70% efficiency of fuelwood is required per 66000 Kg of cassava. 10,000 kg of ethanol and 3600 kg of condensed carbon dioxide is produced per cycle. The schematic diagram in Fig 5 4 below gives the detailed schematics of the ethanol production cycle from cassava roots.

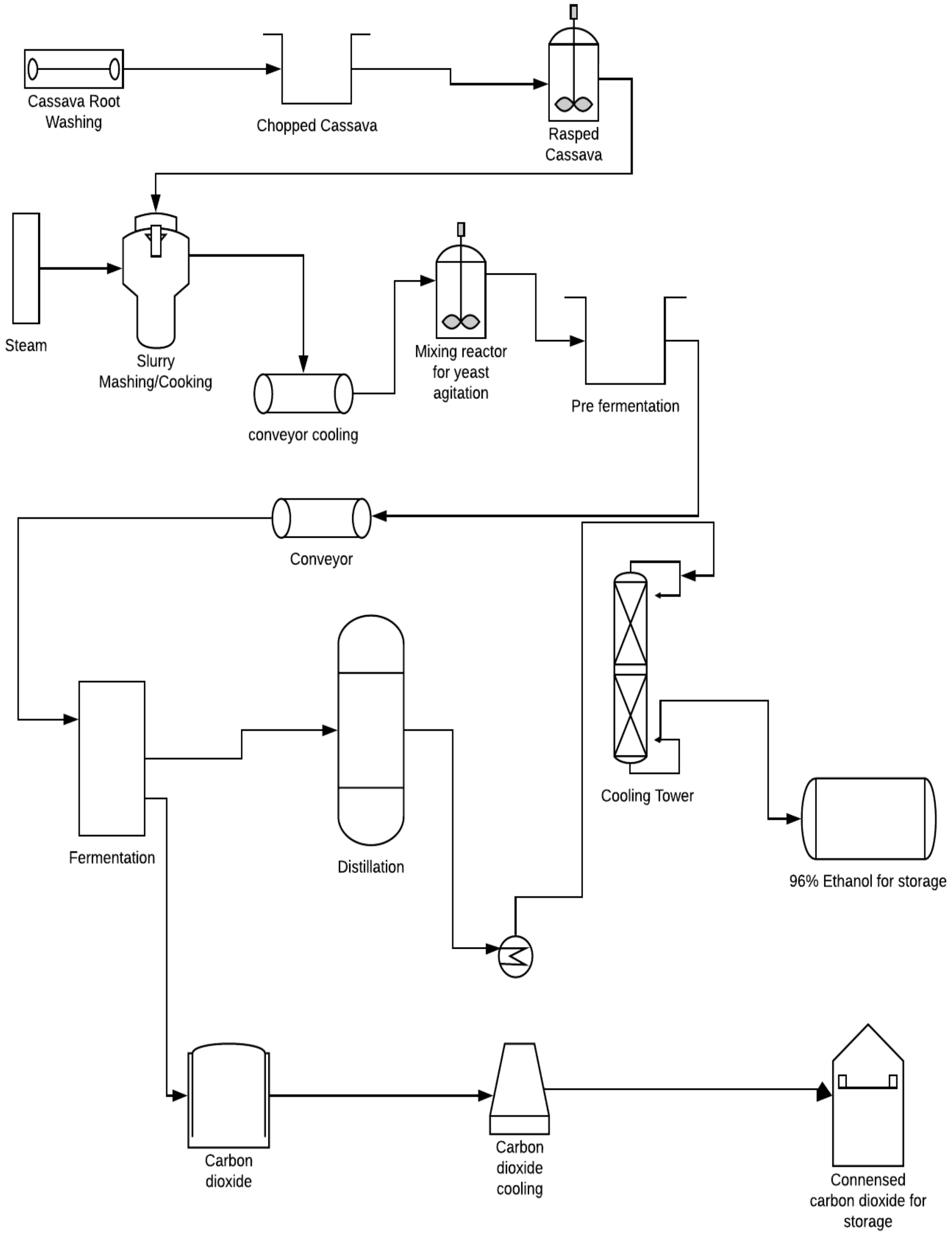

Fig 5 4: Detailed schematic ethanol production cycle from cassava roots.

5.2 Methodology

The energy blocks methodology [53] was used in this study. The research methods included site visits for an initial assessment and a detailed energy audit over a 28-day period. The energy audit first categorises the plant operation into four central units (root preparation unit, mashing/liquefaction, fermentation unit, distillation unit). The energy required for each unit process was measured and recorded. The mass and temperature of the unit processes were also recorded. This was then compared to the designed or theoretical values obtained from the plant manager. The system was then optimized, as Sturm et al. [54]. The process was also optimized with the simultaneous saccharification and fermentation unit [55] instead of the previous individual fermentation and liquefaction units. The optimized results served as the data for a hybridized solar energy model integration [56] using the System Advisor Model. The design was validated for its technical and economic feasibility following the procedure presented by Riggs et al. [57]. Fig 5 presents the methodological workflow used to implement the conceptual model presented in Fig 1. The Fig includes activities (presented in the centre boxes), inputs required to conduct each activity (presented in the left boxes), as well as the outputs or deliverables expected from the completion of each activity (presented in the right boxes). In cases where the objectives defined at the beginning are not attained, feedback loops are implemented to specific activities where possible adjustments should be made in an iterative manner until the objectives are attained.

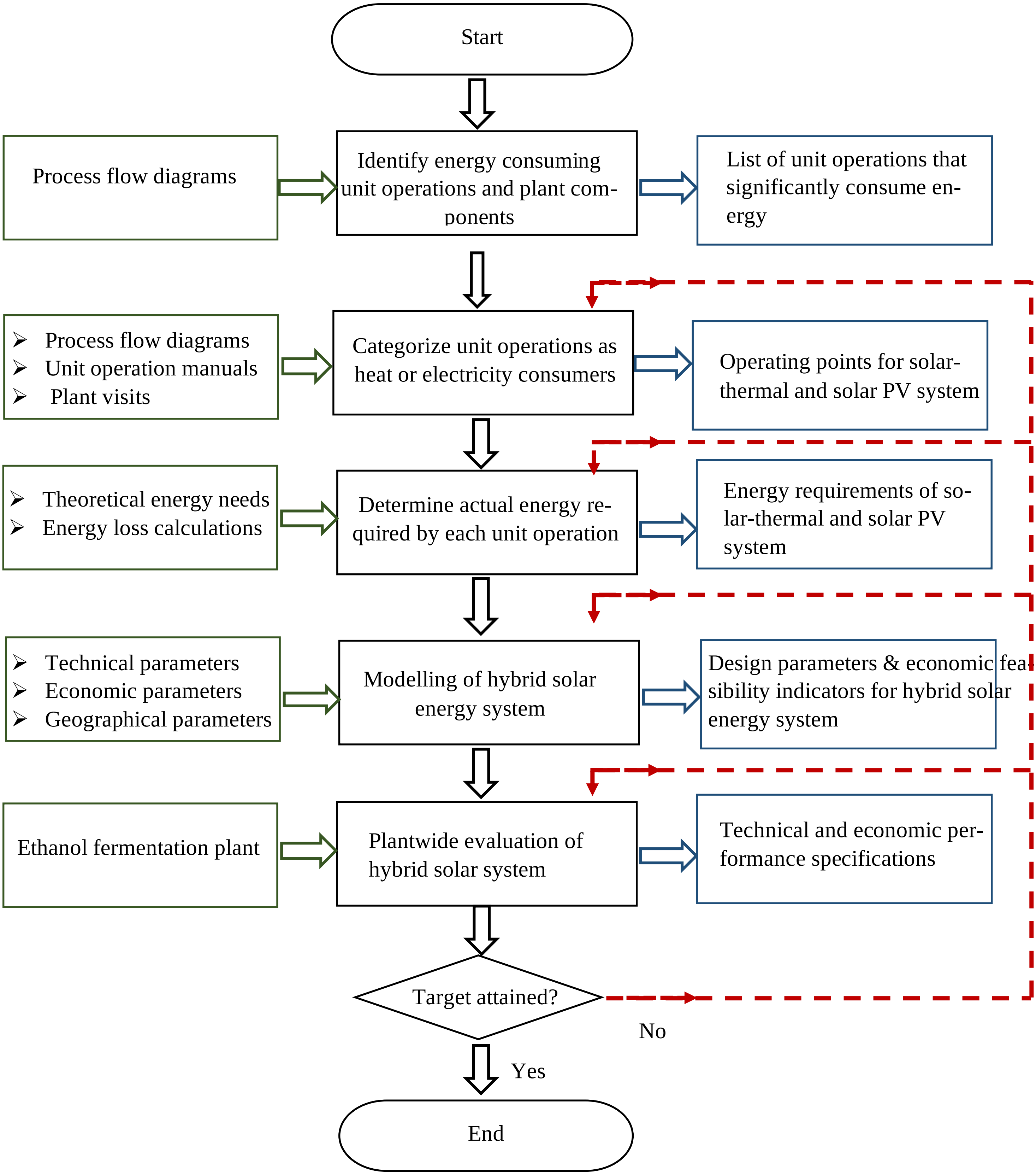

Fig 5 5: Workflow for hybrid solar energy integration in an ethanol plant.

5.2.1 Root preparation unit

75% of the energy in the energy in root preparation unit is from rasping alone. The rasping stage is the only root preparation stage, requiring steam. The slurry temperature must be maintained at 40˚C. The initial temperature is the ambient temperature, as the rasping does not occur in an enclosed area.

The mass of steam used was directly based on the sum of all theoretical energy demands and heat losses in the stage in question, which are described in detail below.

$$Mst = \frac{Q_{DEM}}{\left(\Delta h_e + C_{P,st}\right)\Delta \vartheta} \qquad (1)$$

Steam supply calculations were also done for the mashing and fermentation processes. The condensate left the steam heat exchanger during mashing at a temperature of 107 °C. The water to cool the mixture to 85˚C and 35˚C is used to heat the water to 55˚C for the entire process. The pressure of 250 kPa is kept constant in the rasping stage. Therefore, there is no change in evaporation energy. Potential losses on-site due to leakages or inadequate insulation were not considered.

A baseline temperature of 28°C (ambient temperature) was used for the heat loss calculations related to the discarded condensate. Calculations were conducted as follows:

$$Q_{cond} = M_W C_{P,W} \Delta \vartheta \qquad (2)$$

5.2.2 Mashing/Cooking and Liquefaction unit

Equation 3 below is used to calculate the energy demand for heating the slurry after rasping:

$$Q_H = \left(M_W C_{P,W} + M_C C_{P,C} + M_{cs} C_{p,\mathrm{cs}}\right) \Delta\vartheta \qquad (3)$$

The cooker was approximated as a cylindrical shape, and equation (4) was used to estimate the heat loss for the cooking/mashing stage operation.

$$\dot{q}_{\mathrm{tr,li}} = \frac{2.\pi.l.(\vartheta_{in} - \vartheta_{out})}{\frac{1}{\mathrm{r_{in}} \cdot \propto_{\mathrm{in,li}}} + \frac{\ln\left(\frac{\mathrm{r_{out}}}{\mathrm{r_{in}}}\right)}{\lambda_{\mathrm{s}}} + \frac{1}{\mathrm{r_{out}} \cdot \propto_{\mathrm{out,li}}}} \qquad (4)$$

Where

$$l = \frac{V_{mix}}{\pi r^2} \qquad (5)$$

And the theoretical volume estimated in equation (6) can be compared to the actual volume obtained to be 3.25m^3.

$$V_{mix} = (m_w \rho_w + m_{cs} \rho_{cs} + m_c \rho_c) \qquad (6)$$

The heat transmission at the bottom $\dot{q}_{tr,\,b}$ was calculated using equation 7

$$\dot{q}_{\mathrm{tr},b} = \frac{A\,.(\vartheta_{in} - \vartheta_{out})}{\frac{1}{\propto_{\mathrm{in,ga}}} + \frac{s_S}{\lambda_{\mathrm{S}}} + \frac{1}{\propto_{\mathrm{out,ga}}}} \qquad (7)$$

For calculating the heat transmission of the gas-filled area $\dot{q}_{tr,ga}$, $\alpha_{in,li}$ was replaced by $\alpha_{in,\,ga}$.

For calculating heat losses towards the air in the convective cooling stage Eq. (3) was used. Minimum air demand was calculated using 28 °C surrounding temperature. It was assumed that the material is thinly distributed on the conveyor belt to reach a uniform end temperature of 85 °C and only transferred thermal energy.

5.2.3 Fermentation

The fermentation vats total volume is calculated to be 80.3 m^3. For the heat loss calculations of the vats, heating with steam at 35 °C was assumed. As the vats are not covered, the heat losses toward the room were calculated using natural convection towards the air, with a convective heat transfer coefficient of 10.45 W/m^2 °C. The area exposed to the surroundings was 20 m^2. It was assumed that no heat was lost through the water baths. The only losses accounted for were the losses from the surface of the mix, assuming a uniform product temperature of 35 °C. Calculations were conducted using Eq. (8)

$$\dot{q}_{\mathrm{tr},v} = A\,.\,k_{mix}\,.\Delta\vartheta \qquad (8)$$

Heat losses through the water leaving the system at 40 °C were calculated with Eq. (2).

The heat losses through the wall were calculated as:

$$\dot{q}_{\mathrm{tr},wall} = \left(\frac{A_{conc}}{\frac{1}{k_{conc}}}\right).(\vartheta_{in} - \vartheta_{out}) \qquad (9)$$

The heat losses through the roof were calculated using:

$$\dot{q}_{\mathrm{tr},roof} = \left(\frac{A_{roof}}{\frac{1}{\propto_{\mathrm{in}}}+\frac{s_{ins}}{\lambda_{\mathrm{ins}}}+\frac{s_{conc}}{\lambda_{\mathrm{conc}}}+\frac{1}{\propto_{\mathrm{out}}}}\right).(\vartheta_{in} - \vartheta_{out}) \quad (10)$$

According to the production manager, the ambient temperature is a minimum of 28 °C.

Heat losses through discarding the solid waste had to be based on assumptions as no data on amounts and composition was available.

$$Q_{wa} = 0.8 \cdot m_{wa} \cdot C_{p,w} + 0.2 \cdot m_{wa} \cdot C_{p,mix} \qquad (11)$$

The detailed diagram of the distillation unit can be found in Fig 6 below:

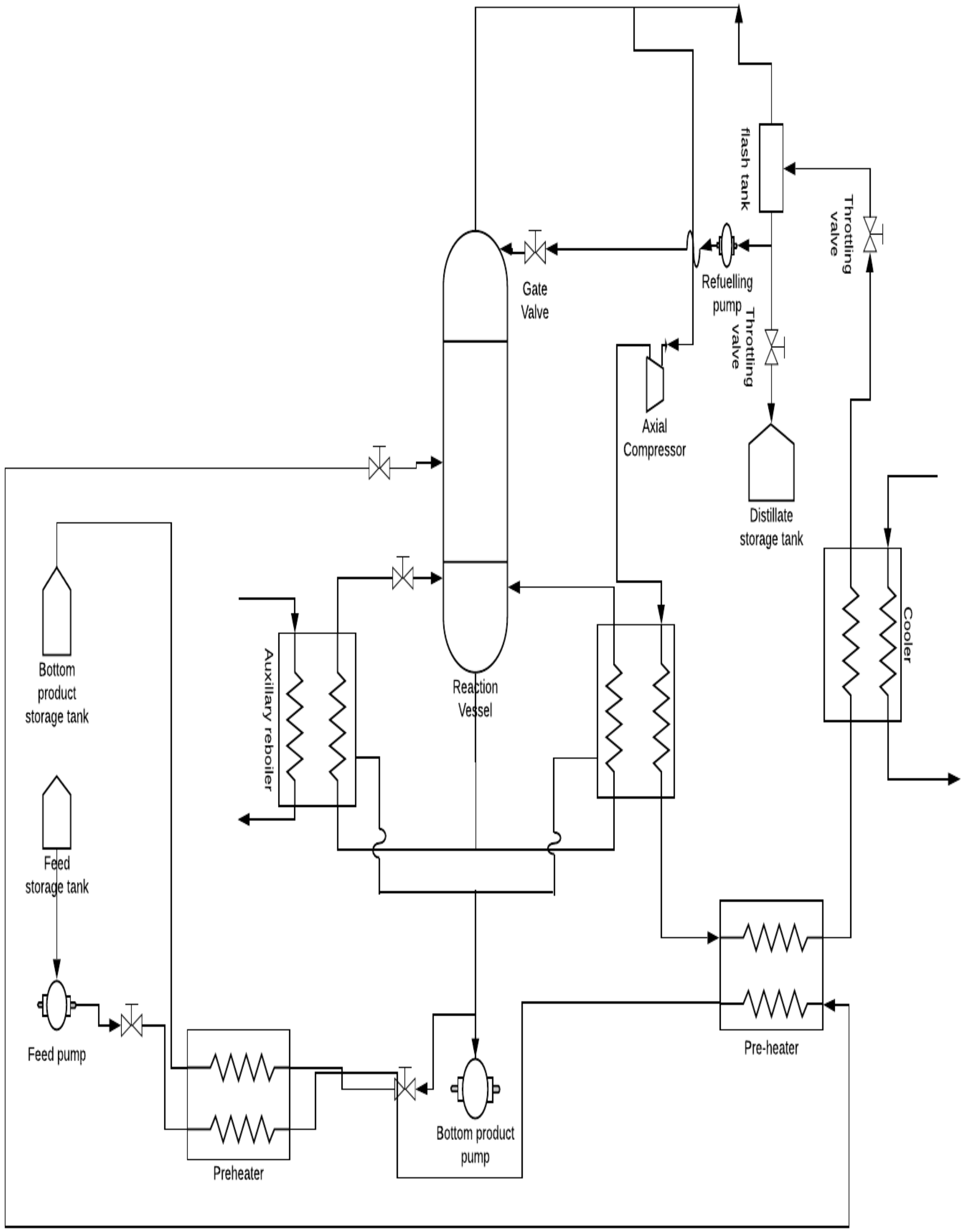

Fig 5 6: Detailed schematic of the distillation process.

5.2.4 Distillation

In determining the heat loss from the distillation column, it is assumed that the temperature is uniform in the space between two plates; the thermal capacitance of the column wall material is negligible, and the convective thermal resistance of the vapour side inside the column is negligible.

The heat transfers between the column wall and the surrounding area are then determined from the relationship for the overall heat transfer coefficient.

$$Q_{Losses} = U_p \ A_O \, \Delta T_P \qquad (12)$$

Where $U_p \, Gani \ gives \ The \ overall \ heat \ transfer \ coefficient$Ruiz, and Cameron [58] as

$$U_p \ = f(h_o, h_i, K_p, A_o, A_i, A_m, t_{ins}) \qquad (13)$$

The temperature difference, ΔT_P is given as

$$\Delta T_P = T_p - T_{amb} \qquad (14)$$

h_o The heat transfer coefficient between the surroundings and the column's external surface is given as

$$h_o \ = f\,(\mathrm{Nu}, K_{\mathrm{ins}}, \mathrm{d_o}, \mathrm{t_{ins}}) \qquad (15)$$

The heat output is calculated with the general expression for convection around cylindrical objects.

$$Q_{loss} = \frac{T_P - T_{amb}}{1/h_i\, A_i + \frac{\ln(ro_{wall}/ri_{wall})}{K_{wall} \cdot A_{wall}} + \frac{\ln(r_{ins}/r_{owall})}{K_{ins} \cdot A_m} + 1/h_o\, A_o} \qquad (16)$$

The column inner surface heat transfer resistance is neglected as the heat transfer coefficient for condensing vapour is significant and, therefore, will have little effect on the overall heat transfer.

For the case considered in this study, the column is hot, and extra reboiler duty is used. Based on the earlier assumptions, heat transfers due to free convection between the surroundings and the external column wall and conduction through the insulation materials are predicted.

For vertical cylinders, the commonly used correlations for free convection are adapted from Holman [59] as:

For laminar flow,

$$\mathrm{N_u} = 0.59(\mathrm{Gr.Pr})^{1/4} \text{ for } (10^4 < \mathrm{Gr.Pr} < 10^9) \qquad (17)$$

For turbulent flow,

$$\mathrm{N_u} = 0.10(\mathrm{Gr.Pr})^{1/3} \text{ for } (10^9 < Gr.Pr < 10^{12}) \qquad (18)$$

Where Gr is defined as

$$\mathrm{Gr} = \left(\frac{H^3 \dot{g} \beta \Delta T}{v^2}\right) \qquad (19)$$

Where the coefficient of thermal expansion of the fluid is

$$\beta = \frac{1}{273 + T_f} \qquad (20)$$

The mean film temperature is

$$T_f = \frac{T_{wall} + T_{amb}}{2} \qquad (21)$$

$$\Delta T = T_{wall} - T_{amb} \qquad (22)$$

T_{wall} is the wall surface temperature; T_{amb} is the ambient temperature; H is the column height; v is the kinematic viscosity; g is the acceleration due to gravity.

Based on the assumptions made, heat loss through the cylinder heads is given by

$$Q_{cylinderheads} = \frac{2(T_P - T_{amb})\pi r_0^2}{\frac{tins}{K_p} + \frac{1}{h_0}} \qquad (23)$$

Therefore,

$$Q_{loss} = \frac{(T_P - T_{amb})2\pi P_S N}{\frac{\ln r_{ins}/r_0}{Kp.\frac{2\pi P_S.t_{ins}}{\ln\left(1\frac{2t_{ins}}{d_0}\right)}} + \frac{1}{\frac{K_{ins}.Nu}{d_0 + 2t_{ins}}.(\pi dins,m.P_S)}} + \frac{2(T_P - T_{amb})\pi r_0^2}{\frac{t_{ins}}{K_p} + \frac{1}{h_0}} \qquad (24)$$

5.2.5 Thermal optimization

The suggestions for process integration developed were based on the location of heat sources and sinks and their timings. Calculations were based on waste heat availability and the source streams' demand. Calculations were conducted using Eq. (15)

$$Q_r = \int\left(m_w \cdot C_{p,w} \cdot \Delta\vartheta; t; t_1; t_{n-1}\right) \qquad (25)$$

The amount of un-utilized waste heat was calculated using

$$Q_l = Q_{wh} - Q_r \qquad (26)$$

With

$$Q_{wh} = \int\left(m_w \cdot C_{p,w} \cdot \Delta\vartheta; t; t_0; t_n\right) \qquad (27)$$

Optimizing the thermal system is split into two main parts; heat loss from the effluent and heat loss from tanks. Heat loss also occurs at the heat exchanger and pipes, but this was too small to be considered in this study. Figures 5 7, and 5 8 below show the heat loss results from the unit tanks and effluent. Comparatively, 45.1% more heat is lost from the tanks than from the effluence. Tanks 205 (liquefaction or mash tank) and the distillation tank recorded the highest heat loss. The primary tank heat loss was from the distillation column in line with the highest height (H) to diameter (D) ratio. The larger the H/D ratio, the smaller the heat loss removal factor (54). Also, the diameter is proportional to the volume flow rate of the gravitational flow; the heat exchange between the layers increases with the increase of tank diameter, explaining the maximum heat loss from the distillation column.

5.2.6 Mass of steam optimization

For the mass of steam calculations, the following approach was chosen:

$$Q_r = m_{ss} \cdot C_{p,ss} \cdot \Delta\vartheta_{ss} \qquad (28)$$

And the mass of water heated was

$$m_w = \frac{Q_r}{C_{p,w} \cdot \Delta\vartheta_w} \qquad (29)$$

5.2.7 Solar Energy Model design

The System Advisor Model (SAM) [60] is a performance and financial model used in this study. SAM makes performance predictions and cost of energy estimates based on installation cost, operating costs, and model design parameters that you specify as inputs to the model. SAM represents the cost and performance of renewable energy projects using computer models summarized in Fig 7.

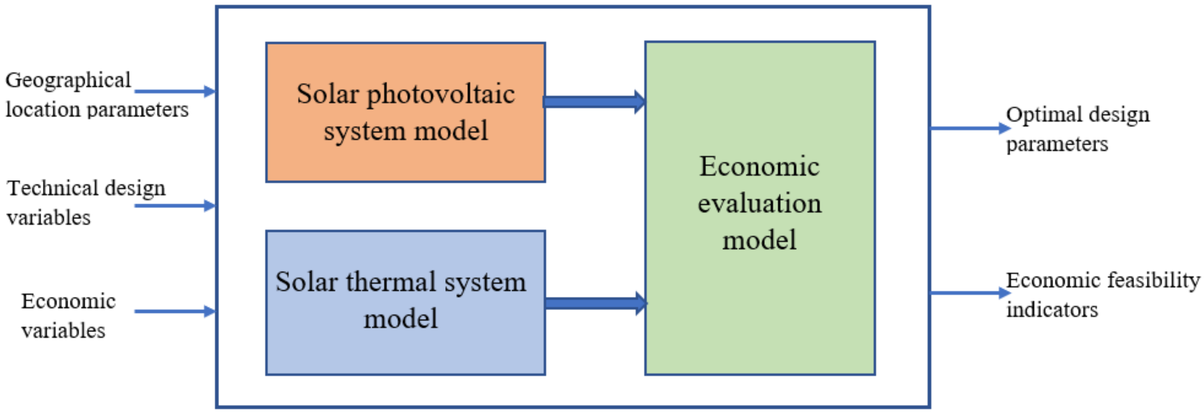

Fig 5 7: Schematic representation of the SAM model for hybridized solar energy model.

The main input parameters for the solar photovoltaic and solar hot water heating models are shown in Fig 8 below.

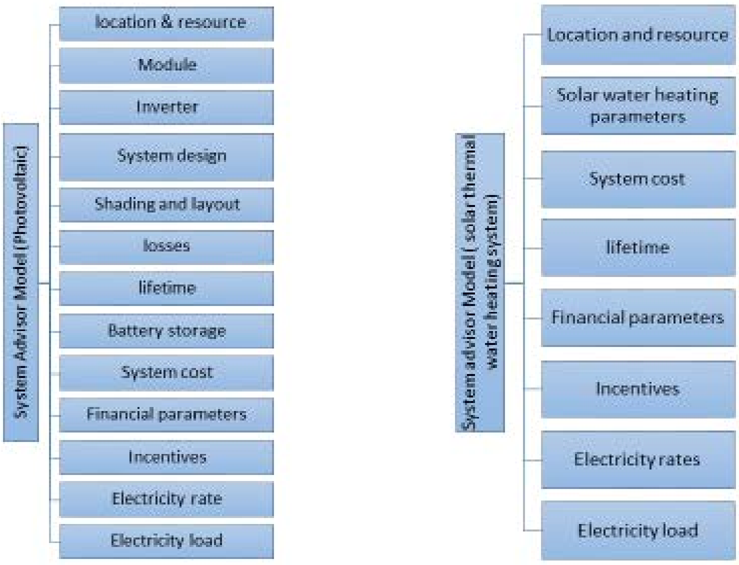

Fig 5 8: Input parameters into SAM for solar photovoltaic and thermal models [61].

5.3 Results and discussion

This chapter discusses the results of the energy and process audit for the optimisation of the process. The thermal efficiency and the mass of steam for the process were optimised, and the results were discussed. The heat loss of tanks and overall heat loss is discussed. The hybridized solar energy models based on the optimised process are also discussed.

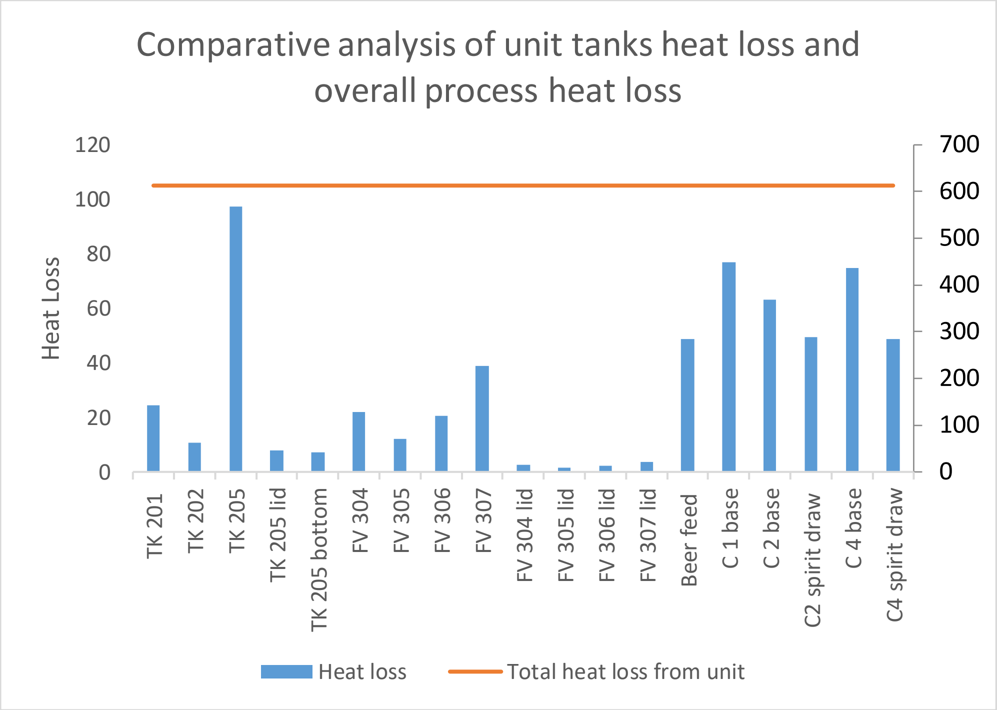

Fig 5 9: Comparative analysis of unit heat loss and overall process heat loss

However, the heat loss from the effluent is mainly from the distillation unit, contributing 59.1% of heat loss. Tank 205 (mashing /liquefaction) contributes 17.2% of the overall heat loss. The heat loss is directly proportional to the mass of effluent in line with equation 2 above. Improved housekeeping is recommended, such as fitting clearly labelled waste containers [62]. Network pinch method / Sequential cross pinch heat transfer [63] is recommended between liquefaction and distillation columns. This will reduce the boiler duty by 18.2% when the heat exchangers are re-sequenced. Retrofitting the entire Heat Exchanger Network (HEN) [64] is recommended, but the operating parameters of the existing network should be considered.

The process is reasonably thermally efficient, as seen in Fig 10 below at 90.9%. The fermentation tank 307, however, recorded the lowest efficiency of 61.7%. Therefore, this tank should insulate [65]or be changed to optimize the process.

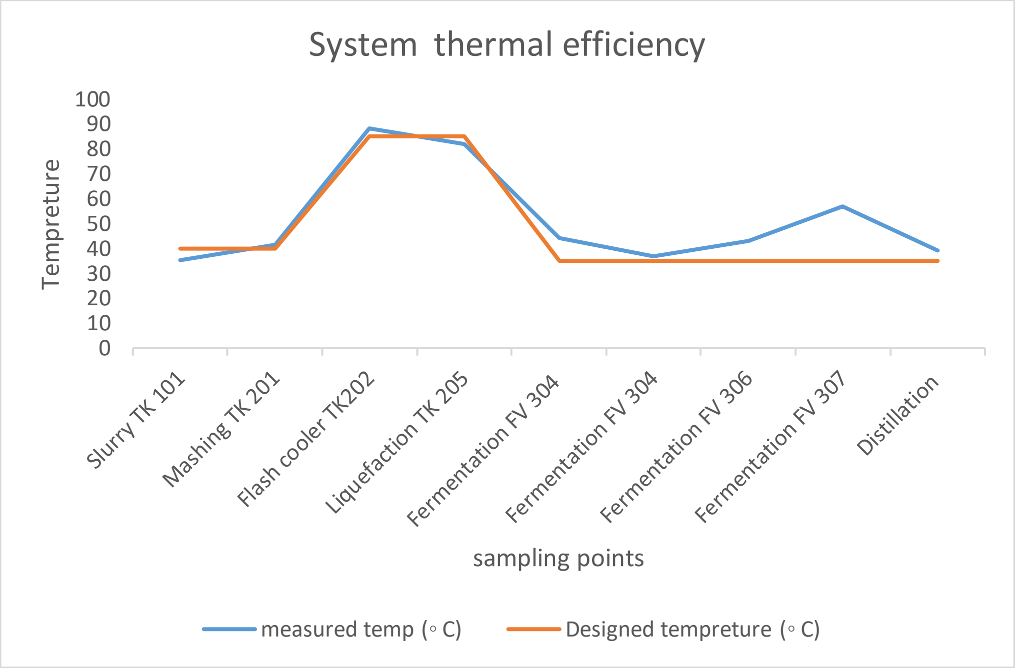

Fig 5 10: Comparative analysis of the designed and measured temperatures.

The root preparation unit was substantially optimized, as seen in Fig 11 below:

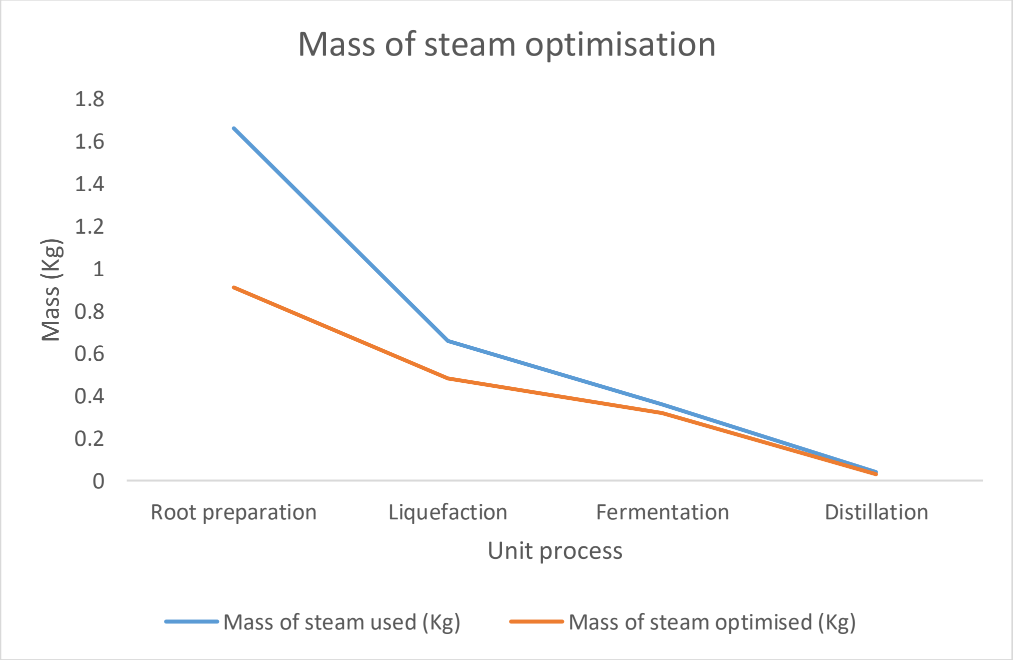

Fig 5 11: Steam optimization at various units.

The mass of steam optimization was conducted for the various units, but the most significant unit is the root preparation unit, as the usage was in excess of 29.2%. The root preparation, in particular, utilizes 68% of the water utilized for the overall process. The root washing phase also needs to be regularized. To optimise the system, the steam injected can also be reduced in the root washing stage. The steam used in the overall root preparation process needs to be automated. Currently, the process is manually done, giving room for many losses from transportation.

5.3.1 Electrical power optimization

For the electrical optimization, the overall power consumption was recorded. Root preparation consumes the highest energy of the six units involved in the electrical processing chain (root preparation, mashing, fermentation, distillation, utilities, and storage). This is due to the rasper, which consumes 67.4% of the total power. Therefore, it is highly recommended that the rasper be replaced with the rasper PS50-100, which is 28% more efficient. Alternatively, only the old motor could be replaced as the other parts are functionally efficient. Releasing pumps (rasper slurry pump and fermenter transfer pump) and cables will also reduce the electrical consumption by 21.3%. Light sensors can also be installed to reduce the time the light is left unutilized. If all these measures are implemented, the electrical consumption will reduce by a total of 38.2%.

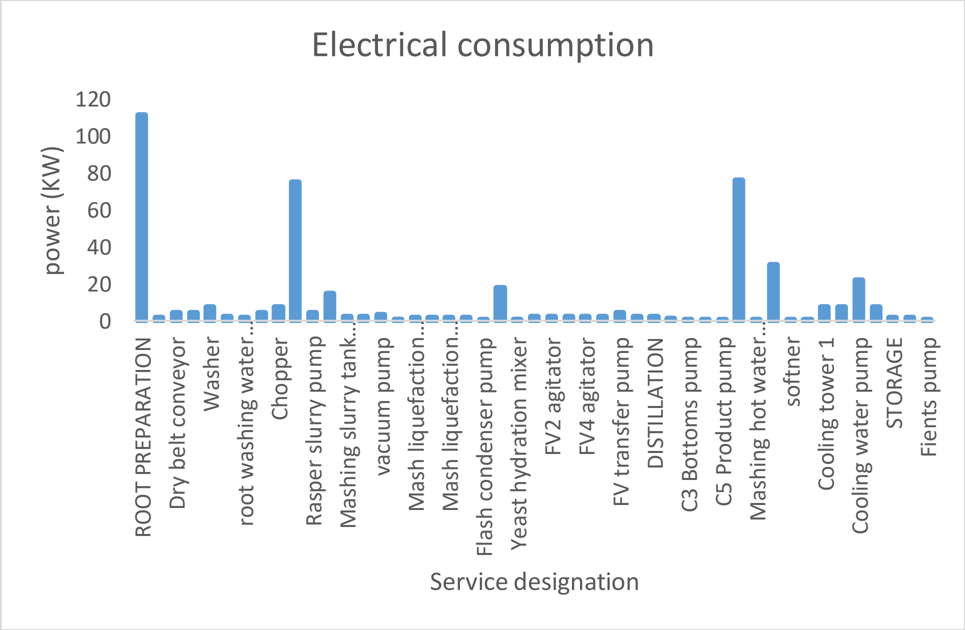

Fig 5 12: Electrical Power consumption pattern for ethanol production.

5.3.2 Model 1 (250 KW solar photovoltaic model)

The photovoltaic panel chosen is the polycrystalline Sun Power SPR-P17-325-COM module is expected to occupy 1.2 acres of land. The panel has an efficiency of 17% with a total irradiance of 1000 W/m^2 and panel temperature of 25 ˚C. If the panel temperature exceeds 25 ˚C at any point, the panel efficiency reduces. The module has an average efficiency of 17.39% but good maximum power point/output of 349. 11 W_{DC}. The summarized solar photovoltaic module parameters are presented in table 1 below.

Table 5 1: Solar photovoltaic module parameters

Solar module parameters	**Value**	**Unit**
Cell temperature	25	°C
Nominal efficiency	17.39	%
Maximum Power	349.012	W_{DC}
Maximum power voltage	43.1	V_{DC}
Maximum power current	8.1	A_{DC}
Open circuit voltage	51.7	V_{DC}
Short circuit current	8.6	A_{DC}
Material	Poly crystaline	
Module area	2.042	m^2

Table 5 2 summarizes the inverter parameters used in this solar model.

Table 5 2: Inverter parameters

Inverter parameters	**Value**	**Unit**
European weighted efficiency	94	%
Maximum (Alternating current) AC power	5000	W_{AC}
Maximum (Direct Current) DC power	5397.58	W_{DC}
Power consumption during operation	21.4856	W_{DC}
Power consumption at night	0	W_{DC}
Nominal AC voltage	120	V_{AC}
Maximum DC voltage	63	V_{DC}
Maximum DC current	130	A_{DC}
Minimum MPPT DC voltage	41	V_{DC}
Nominal DC voltage	47.985	V_{DC}
Maximum MPPT DC voltage	63	V_{DC}

The Sun Power: MIC 320-US 208/240-1X inverter was used. The inverter has an efficiency of 94.4%, maximum alternative current power of 5000 W_{AC}, and 5397.50 W_{DC} maximum direct current power. The DC to AC power ratio is 1.08 confirming the efficiency rate of the inverter. Forty-two inverters are required for this model. The model does not include a battery backup because the models are supposed to be hybridized with the existing diesel generator and steam boiler.

Table 5 3: Solar photovoltaic model sizing parameters.

Model sizing (panels)	Value	Unit
Desired array size	250	kW_{DC}
DC to AC ratio	1.19	
Nameplate capacity	249.88	KW_{DC}
Number of modules	714	
Modules per string	1	
Strings in parallel	714	
Total module area	1458	m^2
String Voc	51.7	V
String Vmp	43.1	V

The model DC to AC ratio of the solar photovoltaic (PV) panel is higher than that of the inverter. This shows that there are fewer conversion losses in the inverter than in the PV panel. The Nameplate capacity is also 99.9% proportional to the desired array size. Only one string was modelled because the objective was to increase power through a parallel connection. On the other hand, a series or string connection increases the voltage, which is not the objective in this case.

The DC to AC capacity of the model is 1.08. This is consistent with the individual inverter ratio. This shows negligible losses experienced in the overall inverter array compared to the individual unit.

Table 5 4: Inverter model sizing parameters.

Model sizing (inverters)	**Value**	**Unit**
Total capacity	210	KW_{AC}
Total capacity	226.698	KW_{DC}
Number of inverters	42	
Maximum DC voltage	63	V_{DC}
Minium MPPT voltage	41	V_{DC}
Maximum MPPT voltage	63	V_{DC}

Simple scheduled washing with water is recommended to reduce losses caused by soiling (dust and dirt) to reduce annual average losses from 5% of the power supplied to 2%. Winds and birds cause soiling.

Table 5 5: Losses parameters.

Losses	**Value**	**Unit**
Average annual soiling losses	5	%
Total DC power loss	3.465	%
AC wiring losses	1	%

On the other hand, the DC and AC losses need technical expertise to reduce this value further. More detail is shown in Fig 13 below.

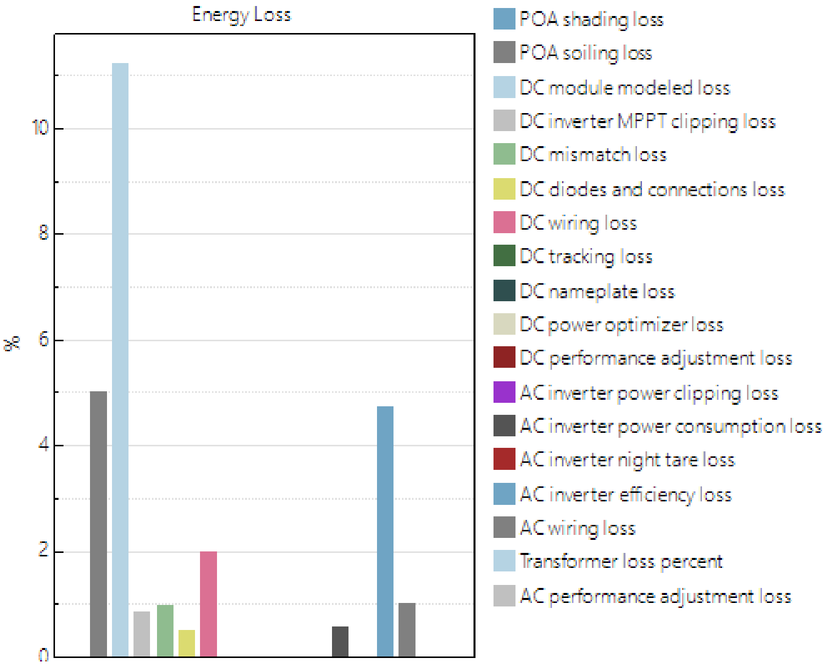

Fig 5 13: Detailed model losses.

Tracking, power optimizer, performance adjustment, and night tare losses were negligible in this model. However, Azimuth tracking is integrated into the design for maximum efficiency. Estimated losses from module mismatch, diodes, and connections, direct current wiring is 3.5%.

The monthly energy production output in Fig 14 below is synonymous with the solar irradiation pattern. The minimum output experienced in June (29.1 MWh/ month) is still above the minimum threshold required for bioethanol production. The model can be scaled up or scaled down if it is required.

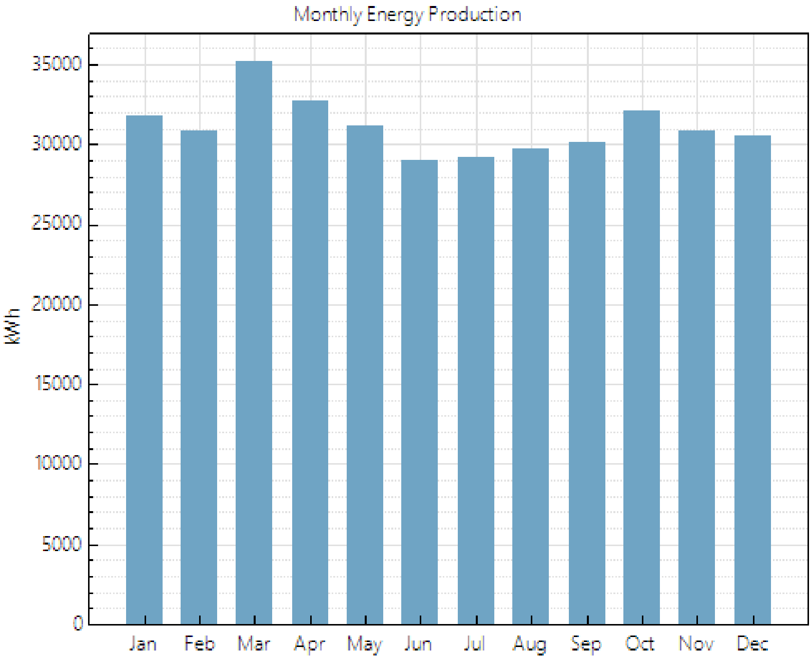

Fig 5 14: Monthly Energy Production.

The model's lifecycle is 25 years at a degradation rate of 0.2%/year in Fig 16 below. The model is estimated to continue producing energy even after the 25 years.

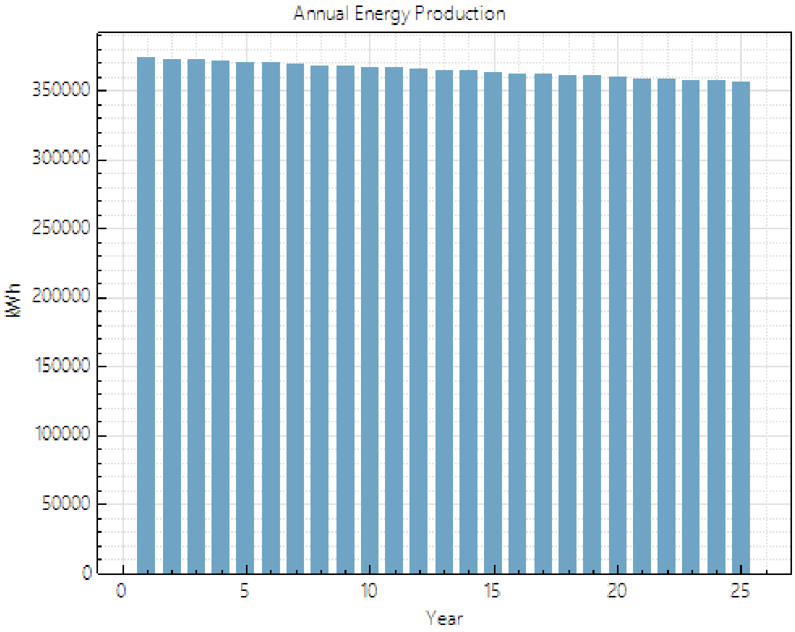

Fig 5 15: Annual Energy production.

Fig 16 shows the positive financial returns on the project. The first year is negative because capital is expected to be invested in the model. The model from the first year onwards records a consistent positive profit.

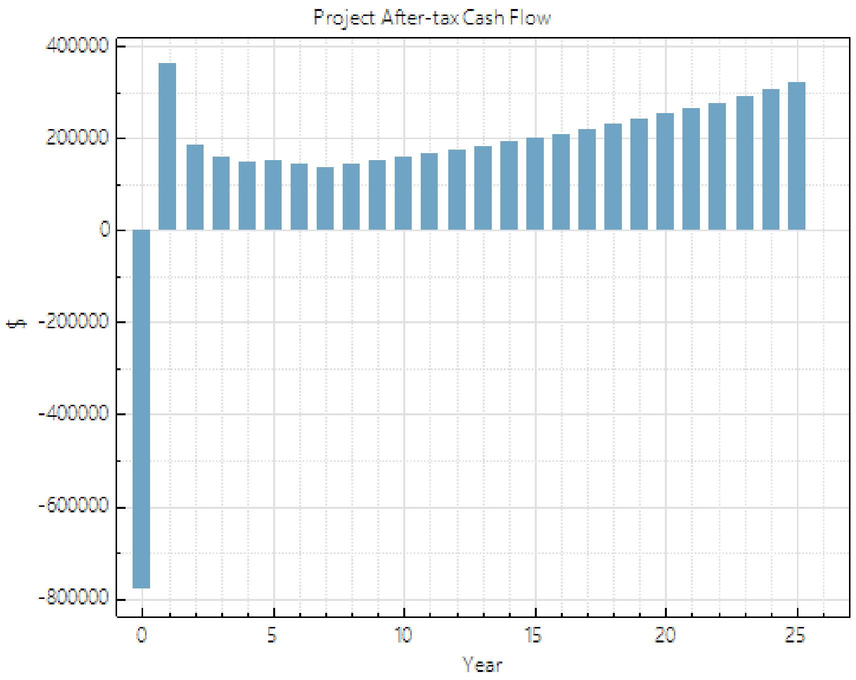

Fig 5 16: Projected after-tax cash flow.

5.3.3 Model (Solar thermal hot water model design parameters)

Table 5 6 shows the model design parameters for the 10000Kg/day solar hot water system. A combination of Diffuse Horizontal Irradiation (DHI) and beam from the Direct Normal Irradiation (DNI) irradiation was considered (in accordance with international standards) in an isotropic medium. This assumes that permeability and permissivity are uniform throughout the model. Glycol boils at 198 °C, making it a preferred choice for this solar hot water system as the maximum designed water temperature of 90°C is much lower . The albedo of 2% indicates that the thermal collectors absorb 98% of the solar radiation. The main design parameter was a 10000 kg/day average daily hot water. Initially the plant manager requested for a 1000Kg/day coupled with the already installed steam boiler. However, upon careful consultations with my supervisors a daily hot water usage of 10000 Kg was adopted as a more suitable standard for an industrial plant. The system duration of storage was also designed for 2 cycles to ensure reliable supply. These figures can be further scaled up or down depending on the prevailing local conditions for adoption or application. In this study supplementary hot water is from a steam boiler. The tilt and azimuth were also calculated with respect to the geographical area of study. The type of solar thermal collector used in this study were 200 glazed flat plate, Integrated solar LLC Rado 412-HP collector. Hot water is required for 8hrs a day. The storage design capacity was for two days meaning 8hr/cycle as requested by the plant manager. This capacity can be further scale up depending on the specific plant operation cycle and requirements. Both beam and diffuse radiation were employed in this design to optimise efficiency.

Table 5 6: Solar hot water model parameters.

Model parameters	**Value**	**Unit**
Total annual hot water draw	3.65E+06	kg/year
Average daily hot water usage	10000	kg/day
Tilt	6	Deg
Azimuth	314.66	Deg
Total system flow rate	0.1	kg/s
Working fluid Glycol	Glycol	
Number of collectors	200	
Diffuse sky model	Isotropic	
Irradiance inputs	Beam and diffuse	
Albedo	0.02	
Total system collector area	598	m2
Rated system size	352.5	KW
Collector area	2.98	m2
FRTa	0.689	
FRUL	3.85	W/m2.C
Test fluid	Glycol	
Rated System Size	352.46	KW

The system was initially designed as a roof mounted system but with the total roof requirement of 598m^2 the roof space was insufficient. The system was hence changed to a floor mounted. Therefore, a floor mounted system was a better option. The coefficient of heat loss of 1 W/m^2 °C from the tank is significantly low as shown in Table 5 7. The outlet water temperature was set at 55 ◦C as requested by the plant manager. A tank volume of 20 m^3 is required for this design. Although the model is a tropical application, the piping was further insulated to further reduce heat loss.

Table 5 7: Solar tank parameters

Solar tank Parameters	**Value**	**Unit**
Solar tank volume	20	m^3
Solar tank height to diameter ratio	2	
Solar tank heat loss coefficient	1	$W/m^2.C$
Solar tank maximum water temperature	90	°C
Heat exchanger effectiveness	0.75	
Outlet set temperature	55	°C
Mechanical room temperature	28	°C
Storage capacity	16 (8h daily)	h

Although the model is a tropical application, the piping was insulated further to reduce heat loss. The calculated pump efficiency of 85% of the current design is relatively higher than the previous pump efficiency of 58% before the solar thermal study. This further increases the need for system optimisation before solar energy system design.

The model energy production is synonymous with the location's weather data, as seen in Fig 5 17 below. This is the useful energy from the collector. A battery backup will flatten the curve if requested; however, the energy production from the system is consistent with the estimated plants' energy requirements with the existing boiler supplying excess requirements. Peak production occurs in the months of March to May, with the minor peak occurring in December. Also, the difference in energy production and consumption from June to October (rainy season) is compensated for in the designed storage capacity.

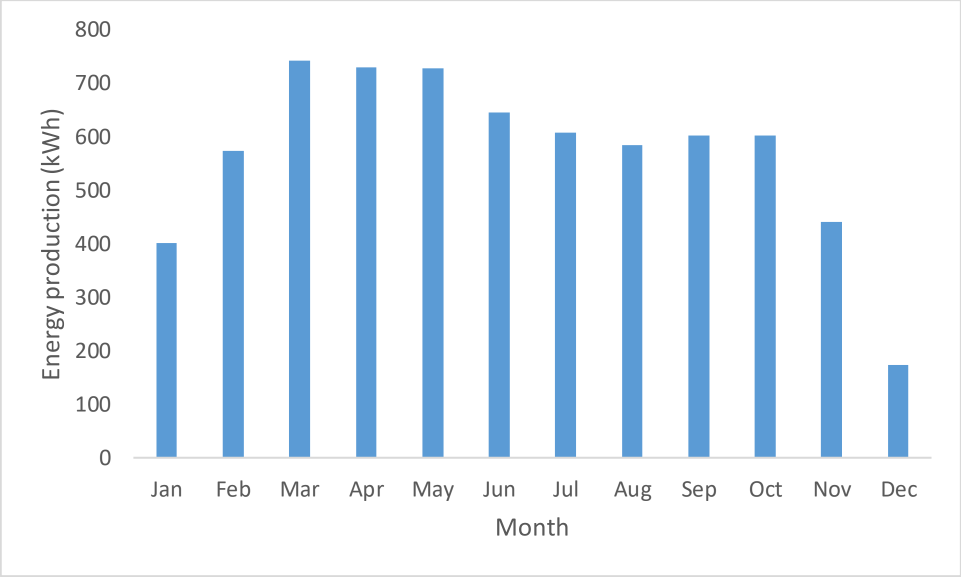

Fig 5 17: Solar thermal monthly energy production.

The annual energy production experiences a degradation of 0.5% per annum. The model was modelled over a 25-year life cycle graphically shown in Fig 5 18 below.

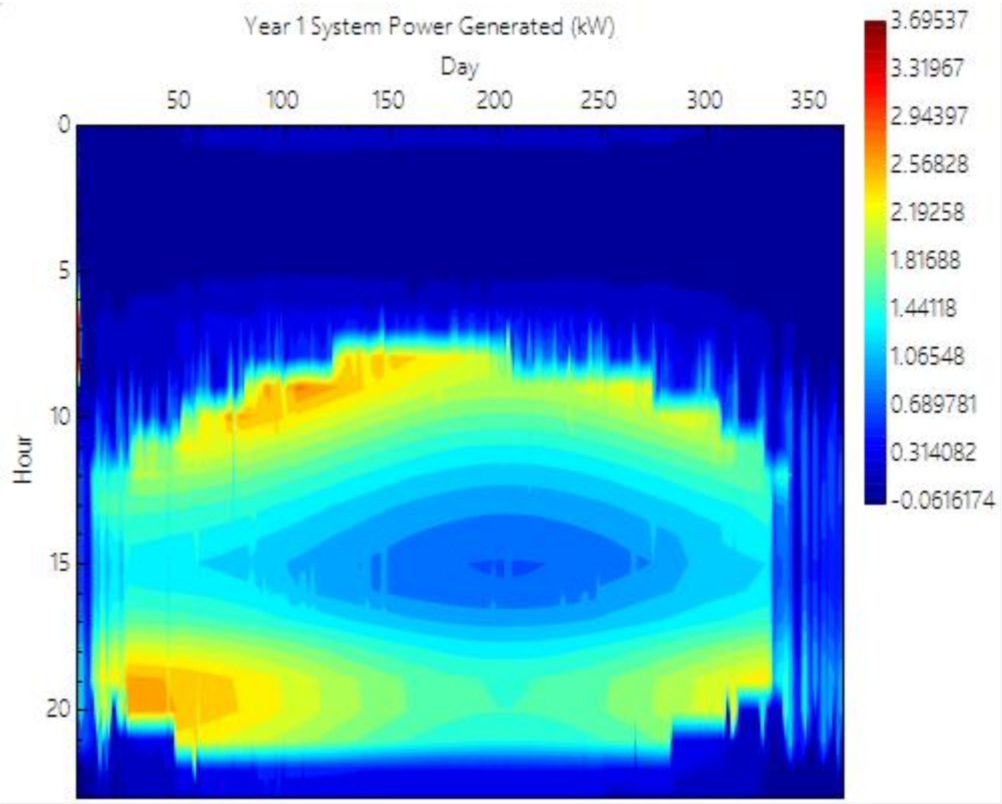

Fig 5 18: Solar thermal annual energy production.

5.4 Economic Analysis

Globally solar process heat plants [66] have been assessed for feasibility within a wide range of industries [67–70] in several studies and found to be feasible and reliable. Solar Industrial Process Heat (SIPH) in the industries confirmed the economic viability of (SIPH) for low temperature (60–80 °C) requirements [71, 72] as is the case for this study. Most of the cost (54.4%) of the direct model cost came from the module. With national subsidies for solar PV modules increasing and Photovoltaic (PV) prices declining continuously [73, 74], this percentage is expected to decline. The balance of model cost forms 17% of the direct model cost, in line with global standards [75]. The model could also be mounted on the factory's roof to reduce the model cost balance to a further 9.6% (reduced mounting model) if feasible. The inverter cost forms 8.5% of the direct model cost and 6.9 % of the overall system cost. The installer margin and overhead were 6.8%, in line with international standards [76].

However, the bulk of the indirect model is from the sales tax. The sales tax accounts for 39.5% of the indirect cost and 5% of the total model cost. Therefore tax subsidies for renewable energy will greatly reduce the overall cost of system and attract more installations. However, the cost of engineering, permitting, and environmental studies[78]cannot vary much but can be subject to bargaining power and contractual agreements [74].

Table 5 8: Solar photovoltaic model cost

Model Cost	**Amount $**
Direct Model cost	
Module cost	159,954
Inverter cost	24,993
Balance of model Equipment	49,986
Installation labour	37,489
Installer margin and overhead	19,994
Contingency	1,462
Subtotal	293,878

Indirect cost	
Permitting and environmental studies	4999
Engineering and developer overhead	12,496
Land purchase	2499
Land preparation	2499
Sales tax	14,694
Subtotal	37,187
Total installed cost	331,066
The total installed cost per capacity	1.32/W_{DC}

Apart from the sales tax, roof preparation, project, and miscellaneous cost, 23.1% of the indirect cost is from engineering or technical cost. The solar photovoltaic models' annual energy production is approximately equal to the annual energy-optimized demand. The capacity factor (a measure of the overall electricity production efficiency) can be further improved by reducing losses. This model is based on automatic adjustment in accordance with the feed-in tariff agreed on during the 25-year lifetime of the project. Therefore, the nominal and real Levelized PPA price can vary depending on the customer's choice relative to the Levelized cost of electricity [79]. Comparing the national feed-in tariffs to the designed model, the model price is 16% cheaper. The existing profit margin can therefore be increased. The actual cost of electricity was 11.5 % lower than the estimated unit cost of production. The size of the debt and minimum Debt-Service Coverage Ratio (DSCR – a measure of ability to repay debt) [80] was not considered in this study as this was not one of the objectives of the investigation. Therefore, the study shows that solar photovoltaic processing of agricultural produce is very economical.

The solar thermal model cost is summarized in Table 5 9 below.

Table 5 9: Solar thermal model cost

Model Cost	**Amount ($)**
Direct Model cost	
Module cost	358,800 $
Storage cost	40,000 $
Balance of model Equipment	1000 $
Installation labour	2500 $
Installer margin and overhead	19,994 $
Contingency	8046 $
Sub total	410,346 $
Indirect cost	
Permitting, construction and environmental studies	8206 $
Project Land preparation, Miscellaneous	12,310 $
Sales tax	20,517 $
Subtotal	41,034 $
Total installed cost	451,380 $
The total installed cost per capacity	1.28 $\$/W_{DC}$

The total cost per capacity does not include land purchasing cost as the land for the installation already belonged to the plant. The solar fraction (a measure of the model efficiency) is 91%. The savings on the model with solar thermal heat is 99.1 %. For the solar thermal hot water model, the collector cost forms 87.4% of the direct model cost, higher than the global average of up to 60% [81]. Compared to the solar photovoltaic model, the balance of the model cost of the solar thermal hot water model should be 5% lower as the prices on the global market is decreasing. However, there import duties and inadequate implementation of incentives render solar thermal systems expensive. Storage is recommended due to sunshine curve throughout the day [82], although the system is hybridized in this case with a steam boiler. Supplementary process heating models should be equipped using phase change materials (PCM) or molten salts [83] to increase reliability. Glycol was used in this model. However, the thermal model storage formed 9.7% of the direct cost. The installation cost, in this case, encompasses the labour, margin, and overhead cost. This forms 32.4% in the solar thermal model but 19.6% in the case of the solar photovoltaic model. This can be accounted to the scarcity of expertise in the solar thermal market in Ghana, making labour more expensive.

Although the capacities of the solar thermal energy and solar photovoltaic models vary, solar thermal cost 0.5% lower than solar photovoltaic power due to inadequate incentives in the sector. However, electricity from the national grid continues to be heavily subsidized in Ghana. In 2019, over 1 billion Ghana cedi's were spent on subsidizing electricity from the national grid [84]. According to the feed-in-tariffs from the Public Utilities and Regulations commission, electricity from the national grid is still the most expensive at 0.23 US$/kWh, followed by solar photovoltaic at 0.11 US$/kWh. Comparing the national feed-in-tariffs to that of the solar photovoltaic model; the model price is 16% cheaper. The tariff for solar thermal is yet to be approved. For the purposes of this study, it is assumed to be the same as solar photovoltaic power.

A functional Analysis System Technique (FAST) [85] diagram was designed for the study (Fig 20). The FAST provides an understanding of how every specific component of the framework provides value with regard to optimizing energy efficiency and integrating solar energy in the bioethanol production plant. The advantage of this approach is that the FAST aids in systematically thinking about research problems, clearly illustrating the system's different functions and showing the logical relationships between the functions and technological solutions. When reading from left to right, the diagram answers the question "HOW"; when reading from right to left, it answers the question "WHY", and when reading from top to bottom, it answers the question "WHEN". Overall, the diagram presents a conceptual framework, which summarizes how plantwide energy requirements are translated into detailed functional and performance design criteria for energy efficiency optimization and solar energy integration.

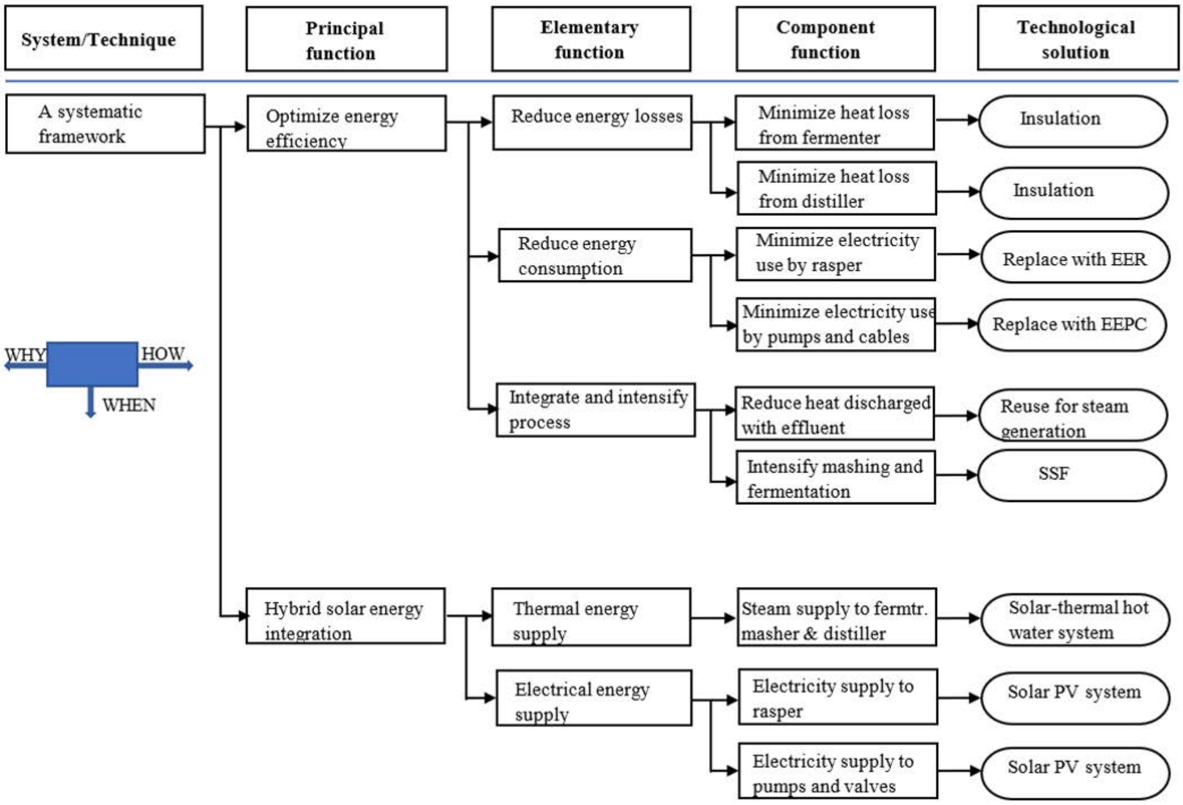

Fig 5 19: Summarised Functional Analysis System Technique (FAST) diagram of the framework.

The systematic framework serves as a blueprint to optimize the energy usage for simultaneous hybridized energy. The energy optimization reduced energy loss and consumption for the process integration. The hybridized solar energy integration was conducted after the optimization measures. The optimization minimized heat loss from the fermenter and distiller. The electricity usage by the rasper, pumps, and cables was minimized. The reuse of heat intensified the process from the effluent in all the units, simultaneous scarification (mashing) and fermentation units (SSF) [86], insulation of tanks, and replacement of old rasper with a modern energy-efficient model. The solar hot water system provided thermal energy for the mashing, fermentation, and distillation units. The solar voltaic model provides energy to the overall process, especially the rasper.

5.5 Conclusion

Returning to the objective posed at the beginning of this study, it is now possible to state that a framework for simultaneous optimization of energy efficiency and integration of hybridized solar energy in industrial plants has been developed. The study makes several noteworthy contributions to science and Ghana’s agro-industrial sector. For the case study considered, the study has shown that energy optimization can significantly reduce plantwide energy loss and consumption by 41.8 %. The functions identified by the Functional Analysis System Technique include The replacement of old pumps and cables to the electrical consumption by 21.3 %; Process intensification by the reuse of heat from the effluent in all the units; simultaneous scarification (mashing) and fermentation units (SSF); insulation of tanks and replacement of old rasper with a modern energy-efficient model. Hot water usage at the root preparation unit was optimized by 29.2 %. 49.2 % (almost one-half) of heat is lost from the mash/liquefaction tank.

One of the more significant findings to emerge from this study is that it is techno-economically feasible to integrate and operate the ethanol production plant with the hybridized solar-photovoltaic and thermal system. For solar energy integration, the study realized that the cost of producing solar thermal hot water is 31.8 % higher than solar photovoltaic power due to the lack of subsidies in the sector. The 250 kW solar photovoltaic model has a performance ratio of 75%. A solar thermal model supplying 100 gallons/day of hot water is required with a thermal fraction of 91%. The framework will significantly support the transition towards an efficient, more sustainable solar-powered agro-industrial sector in Ghana and other developing countries.

5.6 Acknowledgement

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6 GENERAL DISCUSSION

This chapter discusses the overall results of this thesis. The discussion focuses on how the study answers the research questions raised in chapter one of this thesis. Namely:

1. Under what scenarios and circumstances can solar energy be a good choice for integration in cassava agro-processing.
2. Can a novel solar integration framework be developed for the processing of cassava?

6.1 Scenarios and circumstances for solar energy integration in cassava agro-processing.

Several scenarios were investigated in the course of this study; however, two scenarios were further investigated to ascertain whether or not solar energy could be integrated as a reliable alternative energy source in the agro-processing sector. The results indicate that although solar energy has not made significant gains in the agro-processing sector, especially in cassava processing in Ghana, it can be integrated into both small and large scale APS in Ghana as a cleaner, reliable source of energy. The case study for the large-scale agro-processing sector was a bioethanol processing plant from cassava. In the small-scale scenario, the case study was a cassava drying experiment from a designed and developed solar Tunnel dryer (STD) and Chimney Dependent Solar Crop Dryer (CDSCD) for cassava chip drying.

6.2 LARGE SCALE SCENARIO

A novel Functional Analysis System Technique (FAST) framework was developed to guide varying large-scale solar integration in the agro-processing sector. In the large-scale scenario, the crucial circumstances are process optimization, auditing, and techno-economic solar system for the integration. A detailed discussion is found below.

6.2.1 Process optimization

Existing literature supports the assertion as most audits are conducted using the DEA approach [1–6]. I found out that the process had to be optimized, followed by the DEA approach to energy auditing before the hybridized solar energy system could be integrated. These two initial circumstances are crucial for solar energy integration.

The bio-ethanol plant operated on the traditional batch feeding of yeast for ethanol production, which had to be optimized due to challenges such as fluid dynamics-related stress in the fermenter. There was no extra feeding from the beginning to the end of the ethanol production. These dynamics are unchartered for. This had to be replaced with fed-batch feeding to control the microbial growth rate associated with the dynamics. Fed-batch feeding has been applied and validated in several previous studies, optimising the system [7–9]. Further analysis of the exact concentrations is recommended for this case study in future studies.

Current technologies such as simultaneous saccrifaction and fermentation (SSF) are recommended to optimize the process further. Unfortunately, merging the saccrifaction and fermentation processes comes with the challenge of the formation of inhibitors. Previous studies on the challenge have come out with solutions such as using alkaline or some hemicellulose [10–12]. This neutralizes the formation of these inhibitors. Other solutions, such as using thermo-tolerant yeast [13] to withstand the heat build-up and pre-hydrolyzation [14], have been investigated to be prudent in solving the challenge of inhibitors formation in simultaneous saccrifaction and fermentation process in bioethanol production from cassava.

6.2.2 Auditing

From the Data Envelopment Analysis (DEA) based benchmarking approach to auditing the bio-ethanol plant, electricity consumption can be reduced by 41% from recommendations such as using an energy-efficient rasper and replacing old cables and pumps and essential lights within the plant. Therefore, the energy required for bioethanol production was significantly reduced. The DEA-based benchmarking approach is recommended because it is replicable to various scenarios and based on data that can be readily obtained. This study calculated the system's efficiency based on the theoretical energy of the system, unit, or process versus the actual energy of the system, unit, or process. This approach was relatively simple and didn’t require specificialised technical knowledge for application. The agro-processors can therefore collect this data every quarter to ensure their system is optimized and energy-efficient. This approach will reduce the processing cost, thereby increasing the sector's profitability. Also, unlike other approaches like the Stochastic Frontier Analysis (SFA), the DEA approach is comparatively more cost-effective [15, 16]. Unfortunately, unlike other jurisdictions, industrial energy policies are not a widespread phenomenon in Sub-Saharan Africa in general and Ghana in particular. This hinders mandatory energy auditing, which is critical for solar energy integration. [17, 18] also plays a crucial role in process optimization.

6.2.3 System Advisor Model (SAM)

The system advisor model adopted in the design of all the solar thermal and photovoltaic systems used in this study was based on stochastic variables [19–25], which helps the solar system developer design with varying energy and location-specific data. The input data was provided based on the local weather conditions in Ghana, the roof/land space availability, equipment and materials available in Ghana, and technical expertise on energy requirements and affordability. The techno-economic analysis using SAM is very detailed, helping scientists and commerce apply this knowledge with relative ease. Although SAM has an environmental analysis [26] component, this component was not utilized as LEAP software has already been used to investigate the environmental and policy components. The solar photovoltaic and thermal models developed in this study have 75% and 91% performance ratios, respectively. These ratios indicate highly efficient technical feasibility and hence are highly recommended. The results from previous SAM studies [27, 28] are comparable to this study on the technical design. The output efficiency can further be increased or decreased depending on the geographical location of the agro-processing plant.

6.2.3.1 Economic analysis

On the economic analysis using SAM, the study realized that the cost of producing solar thermal hot water is 31.8% higher than solar photovoltaic power due to the lack of subsidies in the sector. In Ghana, the solar energy market has been championed mainly by solar photovoltaic applications. The global price reduction of solar photovoltaic modules is not reflected in the local context due to high importation levies. This notwithstanding, the overall solar production cost is still cheaper than that of solar thermal hot water systems, unlike the global trend [29, 30]. This is due to the limited availability of equipment and materials for installation and limited technical expertise in the area. Like most tropical countries, Ghana does not prioritize domestic hot water usage except for exceptional cases like the medical sector, food & hospitality sector, and processing. However, solar thermal application in the agro-processing sector is crucial to serving as an alternative to fossil-based electricity for hot water generation. Solar thermal systems for hot water production are recommended because the heat produced is utilized directly for hot water production. The challenge of the electricity from fossil and solar energy for hot water production is that it has to be converted to heat which brings about transformation losses. These losses are avoided in the solar thermal hot water production scenario.

6.2.4 The novel FAST framework

A novel FAST framework was developed during this study. It can be used to integrate solar energy into various large-scale agro processing successfully. This means that a variety of crops can be processed using this framework. The advantage of this approach is that the FAST framework aids in thinking and solving research problems systematically, clearly illustrating the system's different functions and showing the logical relationships between the functions and technological solutions. The diagram answers the question “HOW” when reading from the left to the right side. When reading from the right side to the left side, it answers the question “WHY”. Finally, reading from top to bottom answers the question “WHEN”.

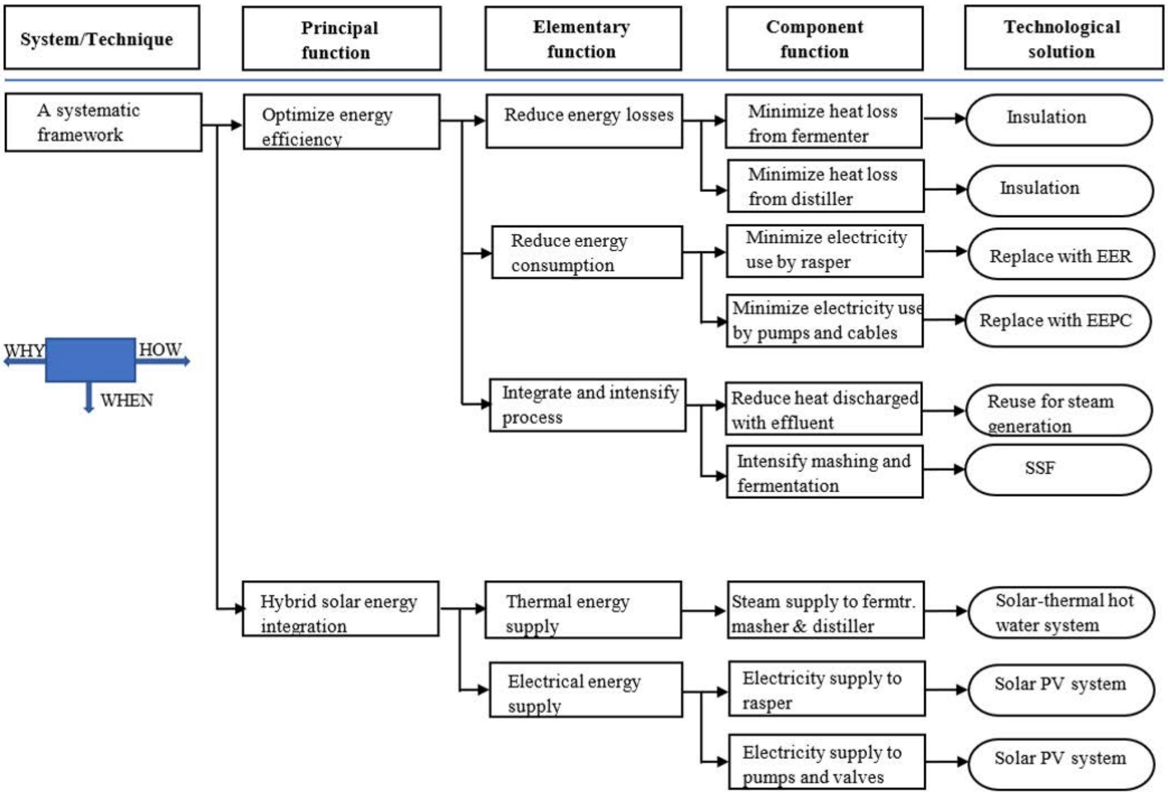

Fig 7 1: Novel FAST diagram developed.

This novel systematic framework has four sub-functions that are replicable and adaptable to different products and processes. However, following the stepwise systematic approach detailed in the framework is essential for optimum results. The principal function encapsulates the optimization process, whiles the elementary function encapsulates the auditing process to intensify the process. However, the component function is very detailed and must be executed in that fashion before the technological solution. Only after these critical functions have been done can solar energy be integrated into the processing. Although the framework was designed based on bio-ethanol production from cassava large scale processing case study, it can be applied to small scale processing or any scale of processing for that matter if the stepwise functions are followed. Overall, the diagram presents a conceptual framework, which summarizes how plantwide energy requirements are translated into detailed functional and performance design criteria for energy efficiency optimization and solar energy integration.

6.2.5 LEAP analysis Policy

In policy analysis, LEAP software was used to model the scenarios [31]. I found out that by 2030, 3.31 million metric tonnes, 9.33 million metric tonnes, and 13.66 million metric tonnes of CO_2 would be avoided in the Business-as-usual, low, moderate, and visionary scenarios. This shows that the highest amount of emission avoided would be in the visionary supply scenario. It also signifies how vital solar energy integration is to reducing Ghana's carbon footprint. The current scenario in Ghana emits 80% more carbons than the projected visionary scenario. The Leap analysis projects a vigorous visionary increase to 15% from the current scenario is needed to boost the solar energy sector, of which the agro-processing sector can play a role. However, policy commitment/prioritization is required to make this target feasible. Currently, there is no clear policy to encourage solar energy integration into the agricultural sector. This finding reemphasizes the importance of policy in promoting solar energy integration in the agricultural sector. Implementation strategies include tax incentives, solar subsidies, promotion of local manufacture of solar equipment, incentivizing solar thermal applications and strengthening the national grid to encourage grid interconnection, net metering incentives, and investment in the solar generation sector.

The investigated field and desktop studies have shown that solar energy can be integrated into the agro-processing sector as a reliable alternative energy source. With the application of the novel developed FAST framework, policies to reduce the cost of the system, audited and optimized agro-processes, and solar energy can be integrated into all scenarios of agro-processing.

6.3 Reflection on methodological choice

The methodologies adopted in this study were existing robust and scientifically proven approaches. The field data collection was integral in shaping the overall scope of the study. Because the study was based on field data and existing methodologies, the output was adaptable, reliable, and scalable.

6.4 Lessons learned

The design of the active solar dryer should be relooked at in future studies as this system performed poorly, contrary to existing literature [33,34]. The ventilation/air circulation design within the dryer should be heated to facilitate the drying process in line with previous studies [35,36]. The blower's speed should also be regulated to ensure optimal performance.

6.5 Positional and personal account of this journey

The social-cultural aspect of the field data collection was very insightful. All the large-scale processors had a male-led management team, whiles one case study of the medium-scale processors had a female manager. In the small-scale processors' case, only one male manager was in that category. This indicates that women are primarily involved in the small-scale sector, but female representation dwindles as the size/capacity increases. Laws and socio-cultural norms mainly determine access to and ownership. Some socio-cultural norms often make it difficult for women to participate in local APS governance as key stakeholders unless project processes are designed to support women. Therefore, gender mainstreaming in agro-processing [37-39] should be prioritized through policy, and implementation by the relevant administrative instructions is highly recommended. In agreement with Colfer [40] society needs to recognize that women and men differ in their knowledge, contribution, and finances towards post-harvest losses through APS and hence should be given equal rights and access.

6.6 Future research

Further research into the design and development of a processing centre for use in off-grid conditions, including a mobile unit carrier and solar energy supply station, is recommended. The unit should be easy to assemble and disassemble and have a battery for energy storage. Other recommended auxiliary parts may include a tool sharpener, Icemaker, wind sifter, engine-driven tricycle, solar water purification, and a milling unit.

7 GENERAL CONCLUSION

The Agro-processing sector in Ghana has experienced growth over the years. Still, the scale of growth can be scaled up by providing a reliable alternative source of energy for the processing. Solar energy applications are not new in Ghana but have not been prioritized in the agricultural sector. This study has shown that solar energy integration into the agro-processing sector is techno-economically feasible for cassava and crop processing in general.

Solar energy integration into the large-scale bioethanol plant did not only reduce reliance on unreliable fossil & significant hydro-based electricity but also increased productivity due to its reliable nature. In the large-scale case study, solar energy integration has been proven to be technically and economically feasible through a novel framework developed from a bio-ethanol application. This developed framework is for the simultaneous optimization of energy efficiency and integration of hybridized industrial solar energy applications. The methodological approach using 3-phase energy audits, FAST framework design, and process optimization reduces the cost of production.

In Ghana, this study has proven solar energy integration to be techno economically feasible for all scales of agro-processors. However, the cost of the system can be further reduced with tax waivers for the equipment and material for the installation. Other challenges such as financing and policy will decelerate the deploration of solar energy into cassava processing.

8 GENERAL RECOMMENDATION AND LIMITATIONS

Solar energy is highly recommended for integration into all scales of the agro-processing sector as it is technically and economically feasible. Further study is recommended on small-scale active solar tunnel drying to optimize performance.

The major limitation was the coronavirus pandemic. The coronavirus pandemic significantly disrupted the initial timelines for the study. Hence the time for the study had to be extended as access to data, library, laboratories, etc., was limited.

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Agro-processing is crucial to reducing post-harvest losses [1-3] and increasing the economic viability of agriculture. However, most agro processes rely heavily on electricity as their energy source. Electricity access and reliability are still challenging, especially in Sub-Saharan Africa, affecting agro-processing. Most farms are located in remote communities without access to electricity. The contribution of the agricultural sector to Ghana's economy has declined from 20.98% (2016) to 17.31% (2019) [5] due to access and reliability challenges for processing. This challenge increases post-harvest losses, thereby reducing the economic viability of agriculture. Reliable sources of electricity should be investigated for agro-processing to reduce reliance on electricity from the national grid [4] and increase efforts in agro-processing.

West Africa is the leading global cassava roots producer, followed by Brazil, Thailand, and Indonesia [6]. In Ghana, a country in West Africa, cassava is a commonly processed crop [7]. It is a staple crop forming a central part of the diet in Ghana. The production area is expanding due to the high demand to feed industries. However, fresh cassava roots contain high moisture content of 60–65% w.b, emphasizing the importance of processing [8]. Solar energy, therefore, presents a cleaner alternative in the tropics for agro-processors [9] of electricity.

This research investigated optimum strategies for integrating solar energy as a reliable energy alternative into the agro-processing sector using cassava as a case study in Ghana. Three investigations were conducted.

The first investigation assessed solar energy implementation in Ghana. This investigation aimed to assess solar energy adoption as a reliable energy source so far.

The second investigation was conducted on integrating hybridized-solar energy into the large-scale cassava-based ethanol plant. This investigation aimed to assess the optimal integration of solar energy into a large-scale agro-processing plant.

The methodology for the first investigation involved developing scenarios using Long-range Energy Alternatives Planning (LEAP). LEAP was then used to model the Low Supply Transition Scenario, Moderate Transition Supply Scenario and Visionary Supply Scenario. The main sectors assessed were heating and cooling applications, equipment manufacture and supply; financing; technical feasibility; policy.

The methodology for the second investigation involved developing a workflow chart to help categorize the order of steps required to complete the bio-ethanol production. It also helped to determine the different steps involved in the process. The Data Envelopment approach (DEA) was used in conducting the audit required for the investigation. A functional Analysis System Technique (FAST) was developed to understand how every framework component provides value in optimizing energy efficiency and integrating solar energy in the bioethanol production plant. A novel seven-step framework was developed. This involved the Goal-setting module: Industrial plant module: Information module: Energy efficiency module: Energy integration module: Data modelling and analysis module: and Data interpretation module. The Solar photovoltaic/thermal system was designed using the System Advisor Model (SAM).

The results indicate that the visionary approach using LEAP futuristic modelling reiterates that a more robust approach is required for solar energy in agro-processing to be met in the first investigation. In the second investigation, the results indicated that the Data Envelopment Analysis (DEA) approach for auditing was replicable; hence, all processors can adopt this auditing approach. Also, auditing significantly reduced process energy loss and consumption by about 41.8% through the integration of an energy-efficient rasper, cables and pumps. The advantage of the FAST approach is that it aids in systematically thinking about research problems, clearly illustrating the system's different functions and showing the logical relationships between the functions and technological solutions. When reading from left to right, the diagram answers the question “HOW”; when reading from right to left, it answers the question “WHY”, and when reading from top to bottom, it answers the question “WHEN”. Overall, the diagram presents a conceptual framework, which summarizes how plantwide energy requirements are translated into detailed functional and performance design criteria for energy efficiency optimization and solar energy integration. Process intensification by using Simultaneous Saccahrifaction Fermentation also optimised the system. The novel framework developed is scalable and replicable.

The first investigation concluded that solar energy deployment is low in Ghana, although there is positive technical feasibility and the required policy for it; Local manufacturing of equipment needs to be encouraged to reduce the overall cost of the system; Incentives, green bonds and subsidies are necessary to make solar energy competitive with fossil prices; Solar heating and cooling sector is insignificant compared to solar power; Power sector deployment is encouraging, but it needs a visionary approach to help meet electrification needs, especially in rural communities. Solar energy solutions can solve the electricity access challenges hindering agro-processing as most farming communities are located in remote areas.

The 7-step novel conceptual framework developed in the second investigation provides the circumstances required for solar energy in agro-processing. This framework can be extended to other crops for application in tropical regions irrespective of the processing scale. Efforts such as; Energy optimization could significantly reduce plantwide energy loss and consumption; Process intensification by using simultaneous saccharification (mashing) and fermentation units (SSF) optimizes the system. Regarding economic feasibility, the cost of producing solar thermal hot water was 31.8% higher than solar photovoltaic power without storage due to the relatively higher equipment cost. This imbalance should be looked at to encourage solar thermal applications in the tropics. The novel framework is scalable and replicable for solar energy integration in the agro-processing sector.

In conclusion, solar energy integration into agro-processing should be further investigated to help reduce post-harvest losses. Findings in this study can be applied to methodologies such as artificial neural networking which is encouraged in further scientific studies.