Clean Technologies and Recycling

Clean Technologies and Recycling, 6 (3): 342–369.
DOI: 10.3934/ctr.2026014
Received: 23 April 2026
Revised: 04 October 2026
Accepted: 02 November 2026
Published: 13 November 2026

https://www.aimspress.com/journal/ctr

Research article

Assessment of oil palm waste valorization potential for sustainable electrification and energy justice in Ngwéi municipality (Littoral-Cameroon)

Vadel Eneckdem Tsopgni [1,2,*], Guy Donald Abassombe [1,2] and Mesmin Tchindjang [1,2]

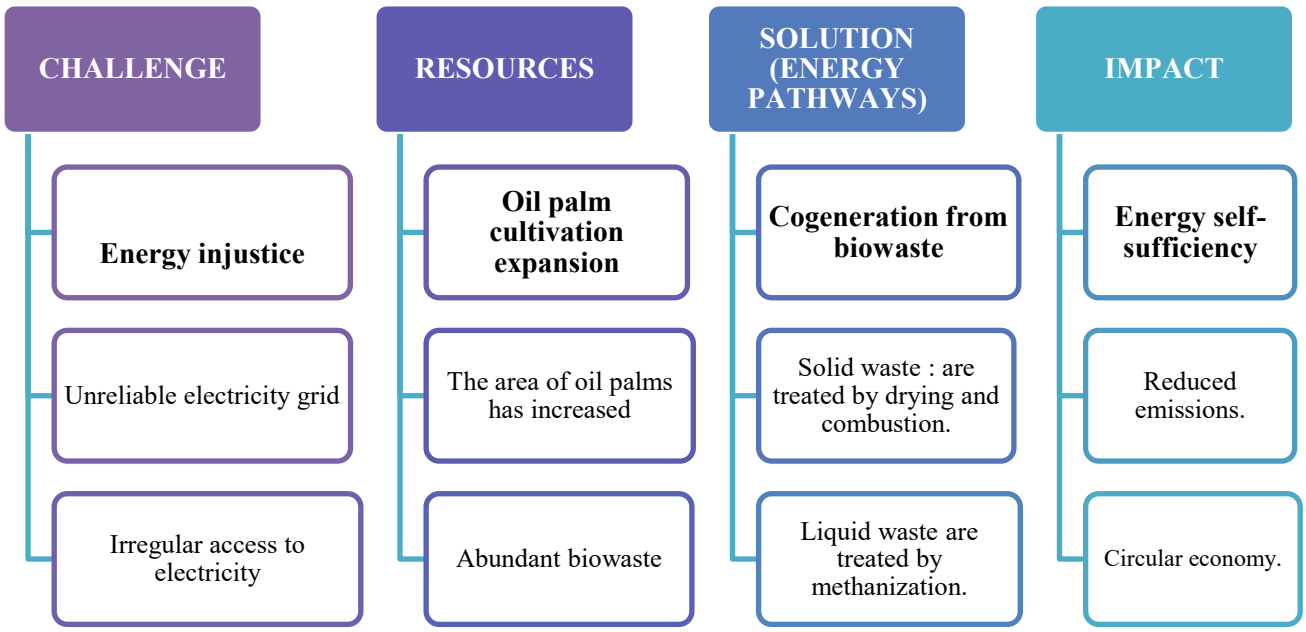
[1] Department of Geography, University of Yaounde 1, 47, Yaounde, Cameroon
[2] Global Mapping and Environmental Monitoring, 337, Yaounde, Cameroon

* **Correspondence:** Email: vteneckdem@yahoo.com.

Abstract: This contribution explores the potential of valorizing oil palm biowaste for improving sustainable energy access in the villages of Ngwéi, Cameroon. This mixed-methods approach includes a critical literature review and questionnaire surveys with 336 households, which represent 20% of the total household population across all 29 villages in the Municipality. It also includes focus group discussions with 139 participants from 6 selected villages: Seppe, Song-Ndong, Ndjock-Loumbe, Bitoutouk, Bomb, and Makek. The data was processed statistically using SPSS 20.0 and Excel 2019, and spatial analysis was performed using ArcGIS 10.2.2 to assess the local energy situation, evaluate the usable biomass from oil palm farms, measure the recoverable energy potential, and estimate the greenhouse gas emissions that could be avoided. The findings show that Ngwéi is a rural area dealing with energy insecurity. Despite being near two three-phase power lines (225 and 90 kV) that lead to the capital, Ngwéi struggles with electrification. Only 21 out of 29 localities are connected to a largely ineffective grid, and 95.6% of households mainly rely on kerosene lamps for lighting. With its palm oil production area, which includes 4012 hectares of palm groves producing 94,474.6 tons of fruit bunches per year, the Municipality could potentially generate about 207,593.603 MWh of energy yearly from palm oil waste, which totals 74,635 tons. Solid waste combustion could theoretically provide 199,946.14 MWh per year, while processing liquid waste through methanization could theoretically produce an estimated 7,647.463 MWh annually. Under the reference scenario of uncontrolled decomposition, the quantity of waste considered corresponds to a theoretical emission burden of approximately 22,187.39 t CO_2e per year. This value is not a net life-cycle estimate of avoided emissions. Thus, recovering 90% of waste poses both environmental and economic challenges. The originality of the study lies in the territorial bioenergetic quantification, coupled with socio-spatial analyses of energy injustice a circular economy and support sustainable energies in Ngwéi and beyond.

Keywords: Oil palm waste; energy transition; energy justice; avoided emissions; GHG; Ngwéi

Graphic summary



1. Introduction

Electricity is a crucial factor for development [1]. It is a public equipment that modernizes rural areas and ensures the qualitative and quantitative development of villages [2]. Indeed, electrical energy improves the living environment and conditions of rural populations. It is considered a prerequisite for any economic growth and contributes to the human development of communities [3,4]. Furthermore, access to this energy is essential to optimize agricultural and industrial production and thus reduce hunger and poverty [5]. Despite this, access to energy is one of the most latent sources of inequality in the world, even if it is less visible than others [6]

Until 2025, access to electricity in Africa was characterized by significant disparities and a persistent energy gap (particularly in rural areas). Indeed, in 2023, more than 666 million people worldwide lacked access to electricity in Africa, with 85% of this population being concentrated in sub-Saharan Africa [7]. The energy divide is particularly pronounced in rural areas, where 451.1 million people remain without access, despite solutions developed to date [8]. In fact, populations not connected to the electricity grid predominantly live in remote, fragile, and low-income areas. In Cameroon, access to energy remains a major challenge for development. In the country's rural areas, 75% of the population lacks access to electricity, even though many live near the power grid [9,10].

As in most sub-Saharan African countries, difficult and expensive access to both traditional and modern energy sources is a major constraint on rural development [11]. This energy insecurity penalizes both households and various segments of the economy. Economically, rural areas are essentially linked to the agropastoral sector, which employs more than 80% of the population in sub-Saharan African countries [12]. To cope with the energy situation, most unfortunately turn to climate-

damaging energy options such as the use of fossil fuels [13]. Indeed, in 2025, more than 2 billion people still depended on polluting and dangerous fuels, such as firewood and charcoal, kerosene, and electric generators for their lighting and cooking needs [7]. In a global context marked by the fight against climate change and the promotion of the energy transition, there is increasing advice to move toward sustainable energy initiatives that capitalize on the strengths of different territories [8]. This situation of unequal access to energy in developing countries falls within the field of energy justice, a conceptual and theoretical framework that has become central to the analysis of sustainable energy transition [14]. This framework emphasizes the importance of an energy transition that is both technically and ecologically efficient and socially just, particularly through the participation of local communities and the governance of energy infrastructure [15]. Despite existing research on oil palm biomass and rural electrification in Africa, few studies combine, at the local level, a detailed quantification of oil palm waste, an estimation of bioenergy potential, an assessment of avoidable emissions, and a socio-territorial analysis based on energy justice. This work fills this gap by demonstrating how an abundant agricultural resource can be leveraged for decentralized electrification, reduced environmental pressures, and local development.

The case of Ngwei in Cameroon is quite telling of such troubling situation in many rural areas of sub-Saharan Africa [16,17]. The Ngwei municipality remains in a state of energy insecurity [13]. Considered one of the country's most important palm oil production areas, palm cultivation dominates the economic landscape and shapes the daily lives of the population, whose entrepreneurial dynamism, living environment, and conditions are very often marked by difficulties in accessing electricity. However, given the need to develop the potential of renewable energies to achieve Sustainable Development Goal 7, it is urgent for rural communities with high agricultural potential to move toward energy alternatives based on local biomass [5,9]. Indeed, agricultural activity is generally responsible for a significant amount of biowaste, which, when properly assessed [18,19], can be used for energy recovery [20–23]. It is in this context that the present contribution aims to explore the potential for recovering biowaste from oil palm production for a sustainable energy future in the Ngwéi area of Cameroon.

Despite its status as a major oil palm production area in the Littoral Region and even in Cameroon as a whole, the municipality of Ngwéi continues to face significant poverty and energy inequality, characterized by very limited access to electricity for farmers and a reliance on fuelwood. This worrying situation considerably hinders local development, exacerbates social inequalities, and fuels increasing pressure on forest resources. Therefore, the central questions of this study are: How can oil palm biowaste be transformed into an equitable and sustainable energy opportunity for the people of Ngwéi? What lessons can be learned from successful bioenergy projects that can be adapted to the context of Ngwéi? Technological advances in biowaste treatment have demonstrated significant potential for the simultaneous treatment of waste and the production of bioenergy. These advances are particularly relevant for palm oil mill waste, where integrated approaches combining treatment and energy recovery offer promising techno-economic prospects [24]. These technological developments underscore the viability of biowaste recovery as a sustainable energy solution. Recent work has shown that this recovery can be considered at various scales (from the laboratory to the industrial scale), highlighting both the energy potential and the deployment constraints. However, the present study differs from this work by combining territorial quantification, socio-spatial survey, and an analysis in terms of energy justice at the scale of a rural Cameroonian municipality. The objective of this study is to assess the recoverable energy potential of valorizing oil palm biowaste, ensuring equitable access to sustainable energy in the municipality of Ngwéi and beyond. To achieve this, the study draws on

theoretical frameworks for energy justice and sustainable energy transition [14,15]. Energy justice is operationalized here through three complementary analytical dimensions that are not employed merely as normative categories but rather as a framework for interpreting the data collected in Ngwéi. Distributive justice is examined through the spatial and social distribution of access to electricity, the energy sources used by households, and the costs associated with energy insecurity. Procedural justice is analyzed in terms of public participation, the transparency of beneficiary selection mechanisms, access to information, and avenues for recourse or challenge. Finally, recognition justice focuses on addressing the distinct needs of households, producers, women, socially marginalized groups, and underserved localities [25]. This approach avoids equating a potential increase in energy supply with the automatic achievement of energy justice. This framework would also be relevant for analyzing the governance conditions of a potential local bioenergy sector. However, it should be noted that transition policies do not necessarily yield equitable outcomes simply by utilizing a renewable resource. They must also specify participatory mechanisms, benefit-sharing arrangements, institutional responsibilities, and safeguards for vulnerable groups. From this perspective, public interventions, financing mechanisms, collective action, and community mobilization can constitute central components of energy justice rather than secondary elements of technological deployment [26].

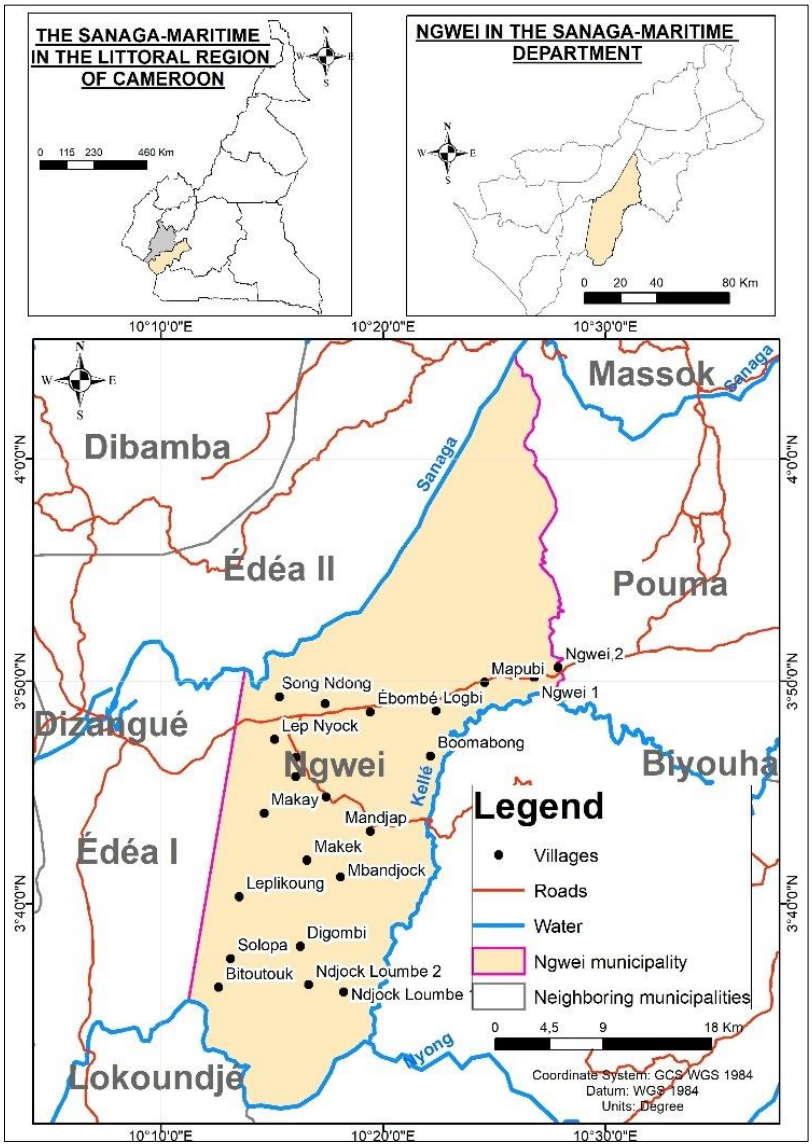
To this end, it is necessary to explore the legitimizing elements of successful bioenergy production models in order to propose suitable solutions for the valorization of biowaste in the Ngwéi Municipality. It is also essential to establish the conditions for replicating these elements at the spatial scale of the study.

2. Materials and methods

2.1. Presentation of the study area: The Ngwéi Municipality

Located in the Sanaga Maritime Department, Littoral Region of Cameroon (Figure 1), Ngwéi is a municipality covering 500 km². It is situated 90 km from the country's economic hub (Douala) and 170 km from Cameroon's political center (Yaoundé). Located in the agro-ecological zone of humid forests with monomodal rainfall, Ngwéi has a humid equatorial climate, suitable for the development of oil palm cultivation. Population projections based on data from Cameroon’s third general population and housing census, conducted in 2005 with results published in 2010, indicate a population of approximately 7200 in the Ngwéi Municipality in 2020. More recent demographic estimates for Cameroon are largely aggregate figures, particularly at the national level, pending the official results of the country’s fourth general population census; this census, launched on April 24, 2026, aims to conduct a systematic count across the entire territory. It is therefore important to note that this population figure for Ngwéi does not necessarily account for recent demographic dynamics within the municipality, specifically migration from other regions driven by the expansion of oil palm cultivation. A mosaic of primary sector activities is found there, dominated by subsistence and cash crop agriculture (primarily oil palm).

The systemic approach made it possible to analyze the complexity of the links between the local electricity situation, the dynamism of the populations, and the potential for sustainable energy development, through the lens of endogenous growth theory [28].



Source: Cartographic databases of the National Institute of Cartography [27].

Figure 1. Location of the study area: the Municipality of Ngwéi.

2.2. Data collection

Scientific publishing platforms (ResearchGate, ScienceDirect, etc.) were used to collect the majority of documents covering a wide range of analytical aspects relevant to the research question. In addition to online resources, physical documents were also consulted. These included theses from university libraries addressing various facets of the topic. The use of these resources provided data on spatial issues, the challenges of oil palm cultivation, and related controversies: oil palm and climate change, and debates on environmental justice in the context of small-scale farming. This research also required fieldwork. This included direct observation of oil palm cultivation and palm oil extraction activities to better understand and analyze the impacts of these activities. The study also incorporated socioeconomic surveys (questionnaires and focus groups).

The questionnaire was administered to 336 households across the municipality's 29 villages

(Table 1). However, the selection process was not based on probability sampling. Households were identified with the assistance of local chiefs and elected officials, aiming for a diverse range of situations regarding palm oil production and energy access. This strategy enabled broad territorial coverage and an exploratory description of the main scenarios observed within the municipality. Nevertheless, it does not guarantee statistical representativeness for the entire household population, nor does it rule out selection bias, particularly given that individuals identified by local authorities may be more visible, more accessible, or more actively involved in the activities under study. Consequently, the quantitative results are interpreted as descriptive trends specific to the surveyed sample rather than as estimates that can be generalized to the entire population of Ngwéi. The 336 surveyed households represent the fraction observed within the survey framework, but the exact percentage of all households can only be determined based on a reliable and up-to-date count of the municipality's households.

Table 1. Number of households surveyed per village in the Municipality.

No.	Villages	Number of households surveyed	No.	Villages	Number of households surveyed
1	Song-Ndong	17	16	Seppe	23
2	Boomabong	5	17	Song-Mbock	16
3	Bomb	14	18	Bitoutouk	14
4	Etouba	7	19	Dingombi	12
5	Logbii	14	20	Mbandjock	9
6	Makek	13	21	Leplikoung	10
7	Makondo I	17	22	Njock-Loumbe I	14
8	Makondo II	12	23	Njock-Loumbe II	10
9	Mandjab	13	24	Solapa	8
10	Mapan	9	25	Ngwéi I	17
11	Mbamble	14	26	Ikonde	11
12	Ndokok-Poubi	10	27	Logbamal	6
13	Nyatjo	8	28	Lep-Nyock	10
14	Poutbiteng	8	29	Makay	8
15	Pouth-Ndjock	7			

Source: Field surveys carried out on the basis of household projections from the RGPH [29].

Focus groups were organized in six villages (Seppe, Song- Ndong, Ndjock- Loumbe, Bitoutouk, Ebombe, and Makek), for a total of 139 participants (Table 2). These villages were chosen based on the diverse nature of oil palm cultivation in the Municipality. The participant groups consisted mainly of oil palm farmers and some members of other sectors (forestry workers, hunters, local and traditional authorities). Discussions focused on three main aspects: the electricity situation in the Municipality, the farmers' experiences with this situation, and energy prospects stemming from the demand for oil palm cultivation and community mobilization. The communities' opinions on the various aspects of the topic helped to open up discussions on sustainable electrification in the Municipality of Ngwéi.

The focus groups comprised 139 participants: 99 men and 40 women. This composition of approximately 71% men and 29% women limits the extent to which the discussions can be interpreted as a balanced reflection of the experiences of the entire population. This is particularly significant for the analysis of recognition justice and procedural justice, as women may face specific energy-related constraints and have different levels of access to community decision-making spaces. Consequently,

the qualitative findings are interpreted as reflecting primarily the perceptions of the participants who actually took part, rather than as an exhaustive or gender-balanced representation of experiences within the municipality.

Table 2. Distribution of the number of participants in the different focus groups.

Villages	Seppe		Song- Ndong		Njock- Loumbe		Bitoutouk		Bomb		Makek		Total	
Number of	H	F	H	F	H	F	H	F	H	F	H	F	H	F
participants	13	11	9	6	18	10	27	7	17	9	9	3	99	40
	54%	46%	60%	40%	64%	36%	79%	21%	65%	35%	75%	15%	71%	29%
Total	24		15		28		34		26		12		139	

M = men; F = women

Source: Conducting focus groups in Ngwei [30].

2.3. Data processing and analysis

The processing of the majority of the data collected during the socio-economic surveys involved SPSS 20.0 software, which was used to code, enter, and analyze the data, generating tables and graphs to illustrate the argument. Excel 2019 software was subsequently used to produce the graphs. To estimate the recoverable biomass from oil palm plantations, the study focuses on palm nut bunches. In this regard, drawing on [31] (who conducted observations and measurements on nut bunches in Côte d'Ivoire), the work uses an average fruit weight of 12.4 kg for the calculations in this study. The quantification of waste is based on a set of reference values collected from the literature. These are the results of measurements carried out on palm fruit bunches in different areas with ecological conditions similar to those of the present study.

The palm oil production process generates four main types of waste (Table 3), representing approximately 80% of the weight of the fruit bunches [32]. These various biowastes possess exploitable calorific values (Table 3), although their high initial water content often necessitates prior treatment for efficient energy recovery: drying (for solids) or methanation (for liquids).

Table 3. Estimation of palm oil waste mass and its calorific value.

Derivatives from exploitation	**Proportion for 1 t of regime**	**Approximate lower heating value (LHV)**
Crude palm oil (CPH)	21%	/
Empty fruit bunches (EFB)	23%	~17.85 MJ/kg (~ 4.72 kWh/kg)
Pressed palm fibers (PPF)	15%	~14.5 MJ/kg (~ 3.89 kWh/kg)
Palm kernel shells (PKS)	7%	~23.6 MJ/kg (~ 6.39 kWh/kg)
Palm oil mill effluent (POME)	34%	~35.7 MJ/m³ (~ 9.92 kWh/m³)

Source: [33, 34, 35, 36].

For palm oil mill effluent (POME), the methanation process is a prerequisite for recovering biogas, the amount of which depends heavily on the composition of the organic matter, the digestion process, and, especially, the solids content.The potential per tonne of POME is estimated at approximately 24 m³ of biogas (containing about 60%–65% methane), with a net calorific value (NCV) estimated at

~35.7 MJ/m³ based on this methane composition [37–39]. Thus, the recoverable theoretical energy potential (*TEP*) from the valorization of this waste is estimated based on the following formula:

$$TEP = Qw \times LCV,$$

where *Qw* represents the quantity of mobilizable waste, and *LCV* represents the lower calorific value of each waste type for energy recovery via combustion.

In the absence of repeated local measurements regarding residue mass, moisture content, calorific value, and conversion yields, the sensitivity analysis relies on plausible scenarios derived from an equatorial climate zone, such as that of Ngwéi [24]. The ±30% variation applied to biomass and the ±15% variation applied to calorific value do not represent statistical confidence intervals; rather, they are intended to test the sensitivity of the estimated order of magnitude to two uncertain parameters.

Table 4. Estimate of GHG emissions released by waste decomposition.

Waste	Emissions (in kg of CO_2e/t of waste)	Observations
EFB	**~ 200 to 400**	It decomposes more easily than others
PPF	**~ 100 to 250**	Higher lignin content, slower decomposition
PKS	**~ 50 to 150**	Very hard and dense, decomposes very slowly
POME	**~ 390**	Based on a global warming potential (GWP) of CH_4 of 25–30 times that of CO_2. That is, 13 kg of CH4 * 30 (GWP) = 390 kg of CO_2e

Source: [36, 38, 40].

These ranges will need to be replaced or refined using local data obtained from measurement campaigns covering the various types of plantations, seasons, and processing techniques. Energy potential estimates are largely based on reference values from international literature due to the lack of systematic local measurements of the calorific value and conversion efficiency of oil palm residues in Cameroon and, particularly, in Ngwéi. This approach, common in exploratory biomass assessments, nevertheless introduces uncertainty related to moisture content, harvesting practices, and the efficiency of processing methods. Therefore, the results should not be considered absolute values but rather orders of magnitude to guide decision-making. Energy recovery from this waste would eliminate significant quantities of emissions into the environment (Table 4). Excel 2019 software was used to calculate potential bioelectricity and estimate avoidable CO_2 emissions in the event of biowaste valorization.

On this basis, the theoretical avoided emissions potential (TAEP), resulting from the valorization of oil palm waste, is estimated using the following formula:

$$TAEP = Qw \times EP,$$

where *Qw* represents the quantity of mobilizable waste, and *EP* represents the emission potential of each waste type under normal tropical temperature and humidity conditions.

The qualitative data from the focus groups underwent thematic analysis. The recordings were first transcribed in full and then reviewed to better identify and utilize community views regarding electricity access, local experiences with energy insecurity in the context of palm oil production, access modalities, and even perceptions of community prospects and expectations concerning the energy

valorization of oil palm residues. The data were subsequently grouped into six main themes: (i) inequalities in electricity access; (ii) experiences with grid instability; (iii) transparency in beneficiary selection; (iv) maintenance constraints; (v) acceptability of new energy solutions; and (vi) local governance and collective mobilization conditions. It should be noted that the primary objective of the qualitative analysis was not to achieve statistical representativeness of opinions but rather to complement local quantitative data in order to better understand and highlight the social and institutional mechanisms underlying energy poverty and inequality in Ngwéi. The qualitative findings were thus triangulated with field observations to strengthen the interpretation of the results. The processing of spatial data and field geographic coordinate surveys was carried out in ArcGIS 10.2.2 software. This processing made it possible to create the location map of the study area and to spatialize the local electrical situation.

The estimation method presented in this study does not entail a full life-cycle analysis of the proposed valorization pathway. It focuses primarily on the theoretical energy potential of the residues and the emissions that could be avoided compared to a scenario of uncontrolled decomposition of oil palm biowaste. Consequently, this approach does not necessarily allow for the quantification of the full range of environmental impacts associated with collection, transport, drying, processing, energy conversion, and facility maintenance. A life-cycle analysis systematically incorporating all these parameters will therefore need to be conducted in a subsequent research phase to compare the various valorization pathways envisaged for Ngwéi and identify the most suitable ones. Among other factors, this analysis must account for equipment energy consumption, collection and transport distances, and emissions associated with drying and conversion processes.

3. Results

3.1. Ngwei, a rural municipality grappling with energy insecurity

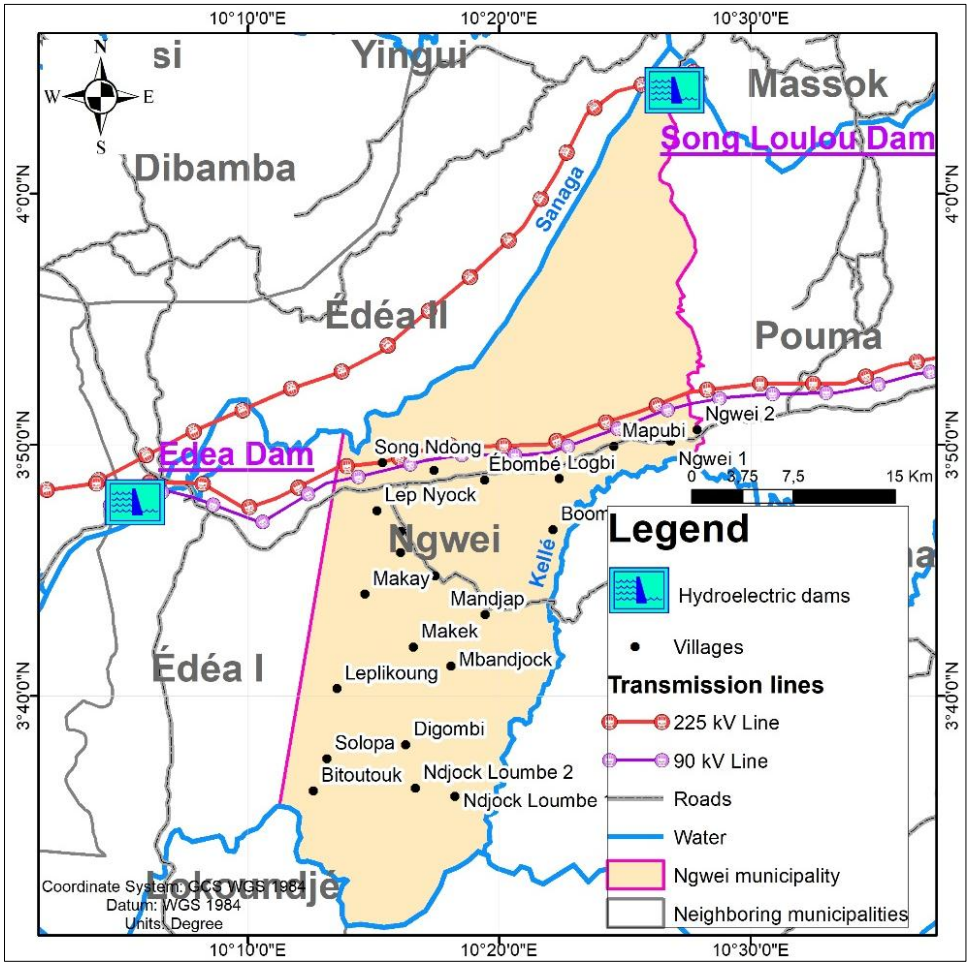
The municipality of Ngwéi, like many others in sub-Saharan Africa, faces what could be described as energy injustice. Indeed, it finds itself without conventional electricity, even though the local resources are essential for Cameroon's Southern Interconnected Grid.

3.1.1. Electrification paradox at Ngwéi: No electricity between two hydroelectric developments

After the Second World War, Cameroon shifted its electricity policy toward hydroelectric power generation. This involved significant investment in large-scale hydroelectric projects intended to supply local communities through a robust and extensive network. These projects notably included the Edéa (276 MW) and Song Loulou (384 MW) dams, both located near the Ngwéi Municipality (Figure 2).

During the construction of these major projects, promises were made to local populations that they would be the primary beneficiaries. However, these promises were not fulfilled, leaving the communities of the Sanaga Maritime region, and the Ngwéi Municipality in particular, without electricity for years. Indeed, two three-phase lines (225 and 90 kV) from the RIS (Rapid Intervention System) cross the Municipality toward the Oyom-Abang substation (in Yaoundé), supplying the country's capital. This is to the detriment of the surrounding localities of these hydroelectric developments, such as Ngwei, which finds itself neglected. According to local authorities, the first electrical installations, resulting from the expansion of the Edéa network, were not installed until the

early 2000s. This followed strong pressure from local residents. Despite this, the electricity situation remains precarious in the municipality and has prompted societal responses, including the diversification of the energy mix.



Source: Field surveys, 2021 and [13].

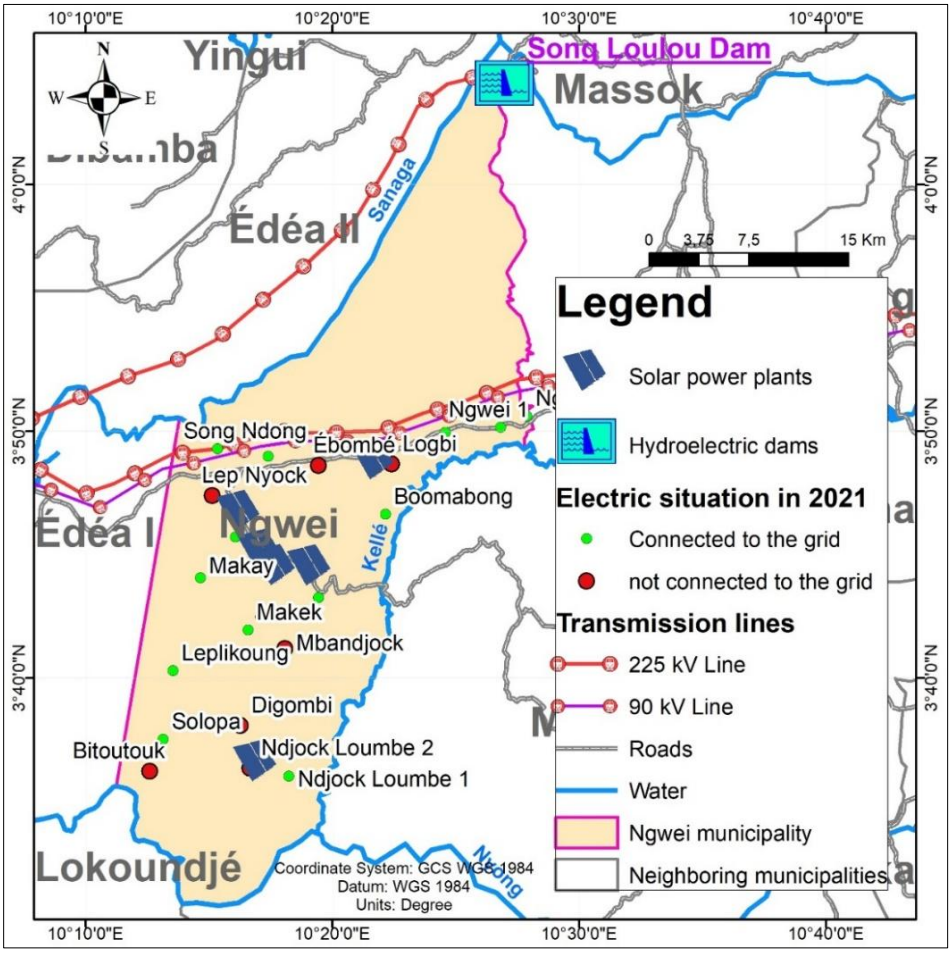
Figure 2. Ngwéi, a municipality at the crossroads of two hydroelectric developments.

3.1.2. Failure of electrification through extension of the Edea network and impetus for a limited solar energy supply

The extension of the electricity grid in the neighboring Municipality (Edea 1) allowed several localities in Ngwéi to be connected to the network of the sole national operator responsible for electricity distribution. Thus, of the 29 localities in the municipality, 21 were connected to the national grid and 8 remained unconnected (Figure 3).

While remnants of the grid can still be seen in most localities, it should be noted that, due to a lack of maintenance by the operator Eneo, electricity supply from the Edea 1 network is now largely inoperative in Ngwéi. Most localities are currently without electricity, and those that still have it face severe grid instability, resulting in power outages lasting for days or even weeks. This lack of maintenance is linked, among other things, to the increasing number of incidents (fallen poles, vegetation fires, vandalism on the line, etc.) and the low rate of investment recovery by the operator

Eneo, based in Edea 1. The numerous requests submitted to the electricity provider have so far been unsuccessful, prompting local authorities to diversify their sources of electricity. Indeed, those who are better off have opted for individual initiatives, including electric generators for some and photovoltaic solar systems for others. However, at the community level, the municipality has benefited from six solar power plants as part of the national project to electrify 350 rural communities using photovoltaic solar systems.



Source: Field surveys [13, 17, 30].

Figure 3. The electricity situation in the localities of Ngwei.

The Municipality currently has six operational solar installations (see photo sheet 1), spread across 5 of its 29 localities: Nyatjo, Mbamle, Logbii, Ndokock, and Ndjock- Loumbe. As part of similar work, field surveys conducted in the municipality between 2023 and 2025 revealed that the number of solar installations remained virtually unchanged compared to the 2019 baseline. However, a more recent technical inventory, covering aspects such as operational status, frequency of breakdowns, specific equipment served, and maintenance conditions, would provide a more accurate picture of the current energy situation in Ngwéi. While commendable, it is worth noting that this energy option is remarkably inefficient. Indeed, it is segregative and exacerbates social divisions within the population. Beneficiaries are selected based on unacknowledged criteria, creating frustration among those not chosen. Furthermore, the limited understanding of the technology and the lack of regular maintenance

of the installations render this initiative just as ineffective as the Eneo grid.



Photo sheet 1. Overview of solar installations and electricity distribution network in the Municipality of Ngwéi. Photo credit, December 2019. *The first three images (above) illustrate some solar installation sites in Ndjock-Loumbe and Logbii Ngwéi. Below, a view of the electricity distribution system using wooden supports.*

3.1.3. Difficulties in optimal access to modern energy

Due to the significant uncertainty surrounding the electricity grid, the use of kerosene lamps is widespread in Ngwei. It is worth noting that with the increasing adoption of solar technologies in Sub-Saharan Africa in recent years, there has been a significant increase in the use of portable mini solar kits in the localities of the Municipality (see photo sheet 2).



Photo sheet 2. A view of some household solar kits in the Municipality of Ngwéi. Photo credit, March. 2021. *The board shows some types of solar panels for household use found in the Municipality.*

Consequently, in Ngwéi, there is significant use of mini solar kits for lighting, charging phones, and charging mini radios. Solar lanterns are now widespread in the municipality: 80.5% of the surveyed population owns them. However, it should be noted that the power range of these kits is low (18–110 W) and insufficient to meet economic needs and services.

Furthermore, in 183 households (69% of the population), battery-powered flashlights are also used for lighting, particularly for nighttime travel and for going to the toilet (usually outside the home) at night. Candles are also used, but to a very limited extent (less than 20% of the population). Beyond lighting, which benefits to a lesser degree from modern energy (albeit modestly), economic activity is severely hampered by this detrimental electricity situation. Indeed, economic activity and social services are severely penalized. This situation of energy inequality is common in rural areas of developing countries, where dependence on wood fuels both environmental and economic problems [16]. The integration of decentralized solutions based on bioelectricity produced from agricultural biomass is one of the major levers for reducing these imbalances.

3.2. Oil palm cultivation: An important source of valuable biomass

Forming the backbone of the Ngwei microcosm, oil palm cultivation is a promising activity for the sustainable energy development ambitions in the municipality.

3.2.1. Oil palm: The soul of the Ngwéi Municipality

The economy and community life in Ngwéi revolve around a mosaic of primary sector activities (agriculture, fishing, hunting, forestry), as well as embryonic commercial and transport activities. Agriculture is the cornerstone of life in Ngwéi, with oil palm cultivation predominating and experiencing explosive growth over the years. Indeed, for several years now, there has been a rather spectacular expansion of oil palm areas in the Municipality (Figure 4). Between 1980 and 2020 (40 years), the area of palm groves has increased 57-fold.

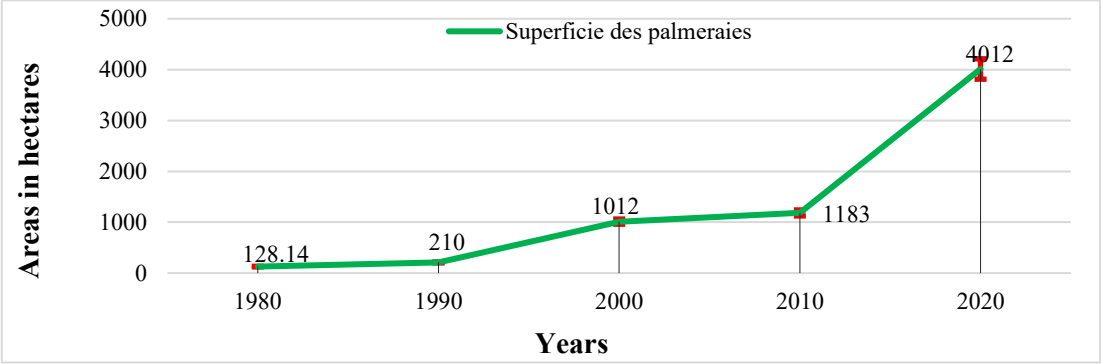


Figure 4. Evolution of palm grove areas in the Municipality of Ngwéi.
Source: Field surveys, 2023.

The area under oil palm cultivation has increased from only about 128 hectares in 1980 to approximately 4012 hectares in 2020. A 10-year analysis of this evolution reveals a disparate dynamic in the oil palm groves of the Ngwéi Municipality. The decades 1990–2000 and 2000–2010 illustrate the beginning of a significant expansion of oil palm plantations in the Ngwéi Municipality. This

dynamic is primarily linked to the proliferation of smallholder oil palm groves (see photo sheet 3), resulting from the temporary breakdown of partnership contracts between agribusinesses and small farmers, and, on the other hand, to the surge in investments in oil palm controlled by local elites and foreign businesspeople. This has contributed to making oil palm cultivation the cornerstone of the lives of the Municipality's inhabitants.

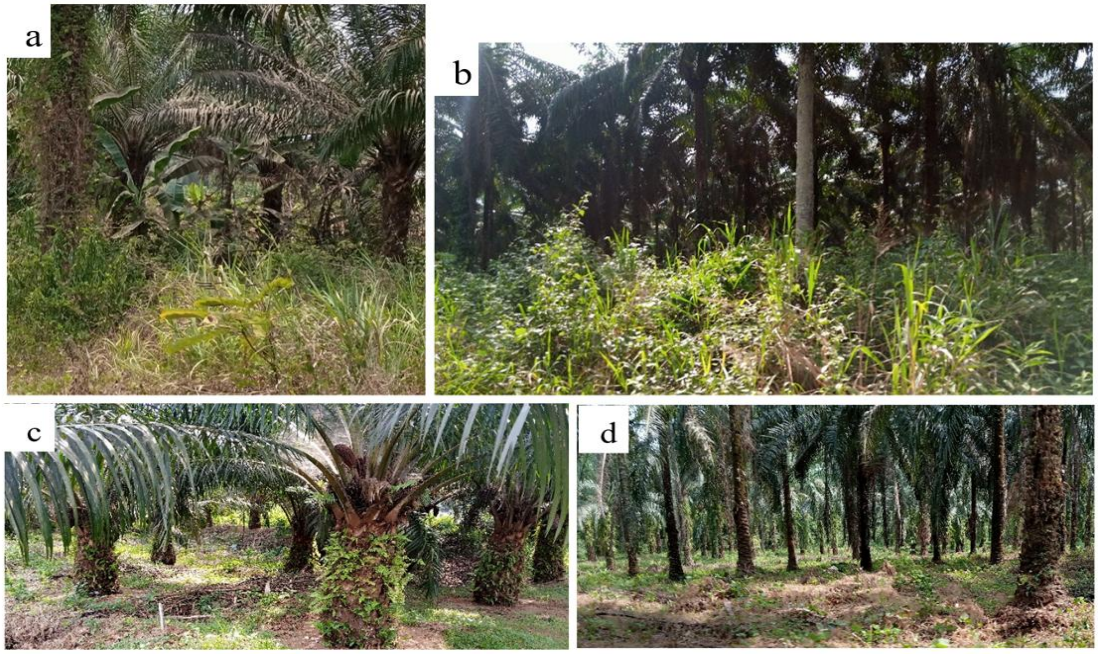


Photo sheet 3. Characteristic features of peasant palm groves (a and b) and those of investors (c and d) in the Municipality of Ngwéi. Photo credit: March, 2021.

3.2.2. Palm nut harvesting in Ngwei: An unsuspected biomass resource

The Sanaga Maritime Department in general, and the Ngwei Municipality in particular, is a center for the exploitation of *Elaeis guineensis* (oil palm), to produce palm oil and its derivatives for both the national and international markets. This activity generates significant quantities of biomass that have not yet been accounted for. However, due to the extensive plantation area in the Municipality, the biomass production linked to the harvesting of the palm fruit bunches would also be significant (Table 5).

Lacking precise data on the surface area of each type of palm grove, this breakdown, based on specific case studies in control plots, allows us to subsequently construct aggregate values for the entire Municipality that are as close as possible to reality. Thus, we can estimate the overall production of palm fruit bunches in Ngwéi (regardless of the season or type of plantation) at approximately 211 bunches/ha/month, or slightly more than 2.6 t/ha/month. For a total annual production over 9 months, plus 3 months dedicated to plantation maintenance activities, we can quantify the fruit bunches at 1899/ha, or 23.55 t/ha per year in the Municipality of Ngwéi. Based on an area of this plant formation estimated at 4012 ha in 2020, the overall production of palm bunches in the Municipality of Ngwei is estimated at approximately 94,474.6 tonnes.

The process of palm oil production from these bunches generates different categories: empty fruit brunches, pressed palm fibers, palm kernel shells, and sludge and palm oil mill effluent. Quantifying

this waste reveals a significant amount of usable biomass in the Municipality (Table 6). Overall, the usable waste from palm oil production in Ngwei is quantified at approximately 74,635 t/year, out of the 94,474.6 t/year of recoverable bunches in Ngwei.

Table 5. Average production of nut bunches per ha/month according to the identified control plantation types.

Gross yields per hectare in maintained "general" palm groves			
Production seasons	**Age range of the palm grove**	**Average number of bunches cut/ha/month**	**Estimated production tonnage (t/ha/month)**
High-production season (two harvests per month)	**5–10 years old**	450	5580
	11–20 years old	450	5580
	>20 years	200	2480
Short season (generally one harvest per month)	**5–10 years old**	350	4340
	11–20 years old	350	4340
	>20 years	100	1240
Gross yields per hectare in poorly maintained, "run-of-the-mill" palm groves			
Production seasons	**Age range of the palm grove**	**Average number of bunches cut/ha/month**	**Estimated production tonnage (t/ha/month)**
Large production season (two harvests per month)	**5–10 years old**	200	2480
	11–20 years old	200	2480
	>20 years	100	1240
Short season (one harvest per month)	**5–10 years old**	100	1240
	11–20 years old	100	1240
	>20 years	40	0.96
Gross yields per hectare in palm groves well-maintained			
Production seasons	**Age range of the palm grove**	**Average number of bunches cut/ha/month**	**Estimated production tonnage (t/ha/month)**
Large production season (two harvests/month)	**5–10 years old**	450	5580
	11–20 years old	400	4960
	>20 years	200	2480
Short season (one haircut/month)	**5–10 years old**	300	3720
	11–20 years old	200	2480
	>20 years	120	1488
Gross yields per hectare in palm groves "tenera" poorly maintained			
Production seasons	**Age range of the palm grove**	**Average number of bunches cut/ha/month**	**Estimated production tonnage (t/ha/month)**
Large production season (two harvests per month)	**5–10 years old**	200	2480
	11–20 years old	200	2480
	>20 years	100	1240
Short season (one harvest per month)	**5–10 years old**	120	1488
	11–20 years old	80	0.992
	>20 years	60	0.744

Source: Field surveys, 2021.

Table 6. Estimated amount of recoverable biowaste from oil palm production in Ngwei.

Empty fruit bunches (t)	Pressed palm fibers (t)	Palm kernel shells (t)	Palm oil mill effluent (t)	Total (t)
21,729.2	14,171.2	6613.2	32,121.4	**74,635**

Source: Calculations based on formulas [31, 32, 33].

The literature on the valorization of these biowastes in Cameroon generally reveals that only pressed palm fibers and palm kernel shells are often valorized, albeit in a rudimentary way. Indeed, these two types of waste are sometimes used to heat boilers and provide supplementary heat energy to firewood in palm oil extraction plants. However, the significant volume of sludge and effluents from oil mills and other waste underscores the urgent need to find innovative waste management solutions, as their disposal and treatment remain major environmental challenges. The optimal valorization of this entire potential of biowaste can also represent an undeniable opportunity for the development of sustainable energy in the municipality.

3.3. Valorization of oil palm waste: An opportunity for sustainable access to electricity, energy justice, and the circular economy in Ngwei

The valorization of oil palm exploitation waste constitutes, in several aspects, a tremendous opportunity to promote energy transition and energy justice in rural localities for those who are often neglected in national energy policies, but whose activity is crucial for several metropolises.

3.3.1. A link between sustainable electrification, energy justice, and the circular economy, driven by the valorization of organic waste in Ngwéi

The aim of the energy recovery project for oil palm residues developed in this study is not merely to increase the amount of electricity potentially available in Ngwéi, but above all to address a threefold challenge: creating conditions for affordable and geographically equitable access and promoting environmental sustainability in the context of oil palm cultivation.

Access to energy refers primarily to the availability and physical possibility of using an energy service, whereas energy justice entails a broader inquiry into the conditions under which benefits, costs, risks, and decision-making opportunities are distributed among different social groups. In the case of Ngwéi, the distributive dimension of energy justice is evident primarily in the unequal distribution of infrastructure and services. The presence of high-voltage power lines near the area does not guarantee actual household access to electricity. Similarly, the existence of six solar installations does not mean that the benefits of this equipment are distributed equitably, given that the facilities are concentrated in a limited number of localities and their operation depends on technical and organizational conditions that are managed unevenly. Harnessing oil palm residues could reduce this spatial inequality, but only if production sites, distribution networks, and tariffs are designed to include currently disadvantaged localities. The procedural dimension concerns the conditions under which such an infrastructure would be decided upon and managed. Data collected reveal questions regarding the selection of beneficiaries, the transparency of decision-making, and the maintenance of the facilities. These factors suggest that the construction of a bioenergy unit should not be viewed merely as a technical intervention. It should be preceded by a documented consultation process, the identification of stakeholders [25,26,36], the

clarification of management responsibilities, and the definition of monitoring mechanisms accessible to the local population. Finally, justice based on recognition [15,41] requires examining groups whose needs risk being underrepresented. Households without grid connections, small-scale producers, women, low-income individuals, and residents of remote areas do not necessarily possess the same bargaining power or capacity to benefit from new infrastructure. In this context, a just approach should include mechanisms to make their specific constraints visible and to involve them in defining energy priorities.

The valorization of oil palm residues proposed in this study can be interpreted as a territorial application of circular economy principles. In the currently dominant model, residues from oil palm cultivation and processing are essentially treated as by-products whose energy potential remains largely untapped. Discarding them into the environment turns a potentially valuable resource into an environmental burden. In the specific case of the Ngwéi municipality, this circularity could be achieved by establishing a local community loop linking oil palm production, residue generation, collection, and energy conversion to the supply of electricity to households. Such a system could simultaneously reduce the volume of waste discarded in the environment, the dependence on certain conventional energy sources, and resource losses within the oil palm value chain. The challenge, therefore, is clearly to move toward a local framework for organic waste valorization capable of generating simultaneous environmental, economic, and social benefits. Integrating circular economy principles and frugal innovation could thus strengthen the inclusive nature of the energy transition in Ngwéi.

3.3.2. Estimation of the theoretical energy potential of residues and the electricity potentially produced

The calculation presented in this section represents a theoretical energy potential based on the mass of potentially recoverable residues and their lower heating value. Given the significant lack of data and general, technical studies in the sub-Saharan context, it does not directly represent the quantity of electricity that could be generated or supplied to households. To move from theoretical energy potential to an estimate of net electricity, one would need to factor in the electrical efficiency of the chosen technology, the facility's annual availability, energy requirements for pre-treatment, auxiliary consumption, storage and distribution losses, and supply seasonality. In the absence of local data on these parameters, this study does not offer a robust estimate of the electricity that could actually be delivered. Oil palm waste possesses valuable calorific potential for developing viable and sustainable energy solutions. However, due to their different natures, the treatment process differs. Solid waste (empty fruit bunches, pressed palm fibers, palm kernel shells) is treated by drying and direct combustion, while liquid waste (sludge and effluents from oil mills or palm oil mill effluent) requires methanation before combustion to produce energy.

- Estimation of the recoverable energy potential from the combustion of solid materials

The calorific values (lower net calorific values, NCV) of oil palm solid waste vary according to their type and water content (Table 7).

With an estimated 42,513.6 tonnes of usable biomass, it would theoretically be possible to recover approximately 199,946,140 kWh, or 199,946.14 MWh, per year in the Ngwei Municipality through the combustion process. This value corresponds to the chemical energy contained in the biomass, not the net electricity produced. The amount of electricity actually available would depend, in particular, on the conversion process, electrical efficiency, internal thermal and electrical requirements, plant

availability, and losses associated with the supply chain. This potential is primarily dependent on utilizing empty fruit bunches of palm fruit, which alone can produce 102,561,824 kWh. However, it is important to note that other resources are not negligible. This is the case with palm kernel hulls, which, although being the smallest resource (6,613.2 t), have the highest net calorific value (NCV), allowing for the recovery of approximately 42,258,348 kWh. Indeed, with an NCV of 6.39 kWh/kg of waste, hulls are particularly effective as a solid biofuel.

Table 7. Evaluation of the energy recoverable from the combustion of solid waste.

Waste	NCV (kWh/kg)	Approximate water content (%)	Quantity of substance (kg)	Total potential energy (kWh)
Empty fruit bunches	4.72	29	21,729,200	102,561,824
Pressed palm fibers	3.89	14	14,171,200	55,125,968
Palm kernel shells	6.39	6	6,613,200	42,258,348
	Total		**42,513,600**	**199,946,140**

Source: Calculations based on [34].

- Estimation of the energy potential recoverable through methanization of liquid materials

Oil mill sludge and effluents differ from the solid waste mentioned above. They have a very high water content, making direct recovery difficult. Composed of 90%–95% water, they have a very low direct energy value. However, they are rich in organic matter and oil residues (up to 0.5%–2%), making them suitable for other forms of recovery like methanization (anaerobic digestion). This recovery process converts the organic matter in these oil mill sludges into biogas, which has a considerable methane (CH_4) content. Thus, with an estimated resource potential of 32,121.4 tones, it would be possible to recover 770,913.6 m³ of biogas (containing approximately 60%–65% methane). Once extracted, this biogas can then be burned in engines or turbines to produce electricity and heat (cogeneration). With an estimated average calorific value of approximately 9.92 kWh/m³, it would theoretically be possible to recover around 7,647,462.912 kWh, or 7,647.463 MWh, after combustion of this resource. Thus, like solid materials, biogas represents a substantial energy source for energy self-sufficiency through biogas production.

By considering all the available biomass in the Ngwei Municipality (regardless of its type or energy recovery technologies used), it would theoretically be possible to recover approximately a total of 207,593.603 MWh per year from the biowaste generated by oil palm plantations. This information constitutes neither an estimate of net electricity generation nor proof of municipal energy self-sufficiency. It should be viewed as an order of magnitude of the harnessable energy content based on the assumptions adopted. Thus, utilizing this waste through cogeneration would allow the Municipality in general, and the palm oil mills in particular, to achieve greater energy self-sufficiency by simultaneously producing thermal and electrical energy for their needs. This approach aligns with a circular economy and "zero waste" strategy for local communities.

3.3.3. Estimation of theoretical GHG emissions associated with the avoided decomposition of residues

The calculation presented in this section does not constitute an analysis of the net greenhouse gas balance of the recovery pathway. It estimates the theoretical emissions associated with a baseline

scenario in which the residues are left to decompose under specific environmental conditions. The resulting figure should not, therefore, be interpreted as a net emission reduction attributable to electricity generation. Such a reduction would require subtracting the lifecycle emissions of the recovery pathway, specifically those associated with collection, transport, drying, equipment operation, combustion, infrastructure, methane losses, and residue treatment. For several years now, for agronomic, economic, and even environmental reasons, oil palm cultivation (with its significant potential for waste production) has become a major issue for sustainable development. In the context of combating climate change and pollution, the recovery and management of this waste is now of paramount importance. However, it is clear that this biowaste is generally disposed of haphazardly in the environment, near factories or along waterways (see photo sheet 4).



Photo sheet 4. Illegal disposal of sludge and effluents from oil mills into rivers in Ngwéi. Photo credit, December 2019 and March 2021. *From left to right, these images illustrate the dumping of palm oil extraction waste into rivers in the villages of Etouha, Dingombi, and Logbii. All the extraction sites pictured are located near water sources. In photo (c), the process of emptying the palm nut cooking vats into ditches that lead directly to the river, which is shown in photo (d) in the village of Ndjock-Loumbe.*

Often left in nature, these residues release significant quantities of greenhouse gases (GHGs) as they decompose, polluting rivers and groundwater. The assessment of avoidable GHG emissions from energy recovery from waste is based on the scenario of landfilling and decomposition in nature. Indeed, leaving waste in nature (particularly for biohazardous waste) generates significant quantities of methane, a potent GHG. Based on this scenario, emission estimates can be made using certain orders of magnitude of equivalent emissions (Table 8).

Table 8. Assessment of avoidable GHG emissions through the recovery of oil palm harvesting waste.

Waste	Average emissions (kg CO_2e/t)	Quantity of waste that can be mobilized (t)	Total emissions (kg CO_2e)
ED	**300**	21,729.2	6,518,760
PPF	**175**	14,171.2	2,479,960
PKS	**100**	6613.2	661,320
POME	**390**	32,121.4	12,527,346
	Total	**74,635.00**	**22,187,386**

Source: Calculations based on [37, 38, 44].

Based on the selected emission factors and the baseline scenario of uncontrolled decomposition, the residues in question correspond to a theoretical emission load estimated at approximately 22,187,386 $KgCO_2e$ or 22,187.39 tCO_2e per year. This value does not constitute an estimate of the net emissions avoided through energy recovery. Indeed, the lack of energy recovery from this waste results in unavoidable methane emissions that contribute significantly to climate change. However, processing the sludge and effluents from the oil mills through methanization systems to capture and burn biogas could reduce these emissions by approximately 80%–90%. This would consequently transform a major environmental problem into a source of sustainable energy.

The valorization of oil palm biowaste thus constitutes an alternative to sustainable electrification in Ngwei. However, it is necessary to ensure the social acceptability of this option in the Ngwei context. Recent studies on the subject, conducted by [43,45], showed that bioenergy projects are sustainably accepted when they are based on transparent and participatory governance models, and above all, when these projects directly benefit local communities: job creation, reduced electricity access costs, infrastructure, etc. This implies that a just and sustainable energy transition cannot be separated from the active participation of local stakeholders. The reflections carried out by [46] on the research on communities and cooperative models demonstrates that community-managed energy solutions strengthen local energy resilience. Based on this, the integrated perspective adopted by this study goes beyond a purely technical or technological approach as an equitable rural electrification alternative. It also, and perhaps more importantly, positions bioelectricity as a tool for reducing inequalities, improving environmental performance, and fostering community governance in the Ngwéi Municipality and beyond.

4. Discussion and perspectives for the transformation of oil palm waste into bioelectricity in Ngwéi

The paradoxical electricity situation in Ngwei, analyzed in this study, reinforces the picture previously painted by the geographer [43]. He poses the question: "How can one not be astonished that the Edéa-Yaoundé power line passes over the villages of the Bassa region without them being able to use it?" [43: 146]. He goes on to specify that it took more than 40 years for the populations of the Sanaga Maritime Department, and those of Ngwei in particular, to benefit from the national electricity grid. According to this author and, subsequently, [13], this situation is linked to the colonial past of this part of the country, which was "hostile" to the French colonial administration. In retaliation, the administration marginalized the region and, after independence, led its leaders to neglect these areas, including Ngwei. Consequently, the municipality finds itself in a situation of energy insecurity. This has paved the way for counterproductive societal responses, which in turn contribute to the fact that approximately 2.1 billion people in 2023 still depend on polluting fuels and technologies for their electrification [7]. This, to a lesser extent, aligns with the reality experienced by the populations analyzed in Ngwei [17]. Indeed, based on a survey conducted among 297 households in Ngwei in 2021 [17], 284 households (or 95.6% of the population) still primarily use kerosene lamps for lighting.

The resolution of this problem in Ngwei, as in several areas where electrification via a centralized grid has mixed effects, requires the development of local resources, in line with the endogenous growth theory [28]. In this sense, off-grid renewable energy systems and standalone solar solutions have already proven effective in their ability to transform many rural communities by providing them with clean and affordable electricity when central grid expansion is ineffective [8]. This, according to previous works [14–16], constitutes a significant anchor point for implementing energy justice through energy transition. Along the same lines, the use of biomass has proven to be a timely alternative in

agricultural production areas, addressing agricultural, economic, and energy sovereignty issues [18–22]. Although this requires a prior assessment of its potential, this valorization of biowaste is, from the perspective of [9], an alternative for affordable, reliable, and sustainable energy, essential for powering households, hospitals, and public services, and for enabling businesses to thrive in underserved or energy-poverty areas. Beyond the estimated energy potential, utilizing oil palm residues could generate interconnected environmental, economic, and social benefits at the local level [24,48–50]. Environmentally, the collection and controlled processing of residues could reduce the haphazard dumping observed around palm oil extraction sites, limit discharges into waterways, and cut some of the emissions associated with organic matter decomposition. Economically, establishing a local supply chain for collection, transport, processing, and energy conversion could foster new activities within the biomass value chain (residue collection, packaging, transport, facility management, etc.). These new revenue streams would complement those arising from the potential implementation of transparent mechanisms for producer remuneration and profit-sharing. Finally, from a social perspective, increased local energy production could improve access to electricity while simultaneously supporting the development of energy-dependent productive activities. However, these benefits are not automatic; they depend on factors such as the scale of the facility, governance mechanisms, and the capacity to maintain the installations.

The assessment of the recoverable energy potential of biomass is generally subject to certain uncertainties inherent in estimation methodologies [33–35]. Even at the level of estimating mobilizable biomass, it should be emphasized that there is no constant production rate of palm waste applicable under all conditions and in all environments [36,42]. Indeed, according to several specialists [23,35,37], production quantities, as well as waste quantities, vary according to numerous parameters: the age of the plantation (the maturity of the palm trees), the harvest yield (which influences the quantity of by-products), and the extraction technology (its efficiency influences the amount of residue). Consequently, underestimating these variables can lead to an overestimation or underestimation of the actual mobilizable potential [36]. Furthermore, the conversion factors used in these estimation methodologies often result from biochemical studies conducted in Malaysia (the world's leading producer). However, in areas that have not benefited from such extensive scientific research, such as Cameroon (which has more or less the same bioclimatic conditions), these results are integrated into models to advance research, while acknowledging the bias related to in situ data in the formulation of recommendations [36]. Moreover, in terms of their valorization, waste has varying calorific values depending on its type and moisture content [20, 22]. Among these wastes, palm kernel hulls (with their low water content) have the highest calorific value, making them particularly effective as a biofuel [21]. Thus, moisture content is a crucial factor, because the lower the moisture content, the higher the calorific value of the waste. The various recovery processes are certainly beneficial because they prevent emissions that are usually released into the environment, but this does not always preclude residual emissions during the process, which are often not accounted for. Indeed, according to [19], following [21], energy recovery does not constitute "zero-emission" processes. We are more in the realm of "low-carbon" scenarios compared to the situation before recovery. In fact, this waste recovery is not carbon-neutral; it still releases CO_2, although unlike the scenario of illegal dumping, which releases methane, a gas with a global warming potential (GWP) approximately 28–30 times greater than that of CO_2 over 100 years [13].

The availability of biomass resources and the existence of theoretical energy potential are not sufficient to ensure the performance of a community bioenergy system. The quality of institutions can

influence the capacity to establish rules, ensure transparency, coordinate stakeholders, secure investments, and guarantee equipment maintenance. Recent studies on bioeconomy demonstrate a positive association between institutional quality and the performance of bioeconomy sectors [43], while research on national economies highlights the combined importance of institutional quality and democratic governance for environmental performance [44]. In the case of Ngwéi, these findings from the literature cannot be directly applied as empirical proof. The study does not measure institutional quality, political trust, administrative capacity, or the performance of local organizations using standardized indicators. Nevertheless, it identifies several institutional conditions that warrant further examination: clarifying responsibilities among the municipality, traditional authorities, producers, electricity operators, and potential managers of the bioenergy unit; ensuring transparency in beneficiary selection; defining a pricing mechanism; securing funding for maintenance; and establishing a local monitoring and grievance redress system. The hypothesis of community-based bioenergy in Ngwéi must therefore be formulated as a conditional hypothesis. It could contribute to a more equitable energy transition if the necessary distributive, procedural, institutional, and financial conditions were met. However, available data do not yet allow us to confirm that these conditions are currently satisfied. The gender imbalance in focus groups also necessitates particular caution when interpreting results regarding participation and recognition [47]. The underrepresentation of women may lead to an underestimation of certain constraints related to household lighting, cooking, fuel collection, caregiving, or participation in energy-related decision-making [16]. Future research should organize separate groups or interviews specifically targeting women, female-headed households, and groups with limited access to institutional spaces.

However, certain uncertainties and sensitivities within this study should be noted. Indeed, the results indicate an estimated theoretical bioenergy potential of approximately 207,593.603 MWh/year; harnessing this potential could theoretically avoid emissions of 22,187.39 t CO_2e/year for the Municipality of Ngwéi. Yet, these figures rely on technical coefficients and NCV derived from studies conducted in Malaysia, Ivory Coast, or elsewhere, introducing significant uncertainty [31,33]. To mitigate this, a sensitivity analysis involving three scenarios (low, medium, high) is essential, given the uncertainty regarding the mobilizable biomass. Yields vary considerably depending on the age of the palm plantations, maintenance practices, and season [23,36]. Assuming a ±30% variation in available biomass, the potential ranges from 145,315 MWh/year (low) to 269,872 MWh/year (high). Incorporating a ±15% variation in NCV [34, 42] widens the range to 123,500–310,400 MWh/year, representing 0.6–1.5 times the central value. Sensitivity results should be interpreted as an exploration of parametric uncertainties rather than as a probabilistic interval. However, these ranges are based on calculation assumptions rather than on a local measurement campaign. The analysis should therefore be supplemented by varying parameters such as electrical yield, annual plant availability, moisture content, collection and storage losses, and the fraction of residues that can actually be mobilized. Consequently, the values obtained should be viewed as exploratory orders of magnitude rather than as precise production forecasts. This range confirms that the theoretical potential remains significant but highlights the need for local measurements of yield and moisture content. Furthermore, the estimated 22,187.39 t CO_2e/year of avoided emissions corresponds to a scenario of uncontrolled decomposition, in which methane (with a GWP of 28–30 over 100 years) is released [13]. However, energy recovery is not a "zero-emission" process, as combustion releases CO_2, and methanization produces both CO_2 and residual CH_4 [19]. For sludge and effluents (BEH), biogas capture and combustion reduce emissions by 80%–90% [5,37], representing an avoidance of approximately 10,022–11,275 t CO_2e/year out of

the initial 12,527 t. For solids, assuming 90% efficiency, the avoided emissions would be around 8694 t CO_2e/year. The range of 15,000–21,500 t CO_2e/year should not be presented as a net climate benefit. At most, it represents an exploratory variation in the theoretical emissions associated with the baseline scenario. Estimating the net climate benefit would require a life-cycle analysis covering direct and indirect emissions from the collection, processing, and energy conversion chain. However, these uncertainties do not call feasibility into question [30], though they do necessitate net accounting and the use of local data [36]. Energy justice [24] and energy communities [44] serve as levers for participatory governance. Endogenous growth [28] supports local value creation, provided that individualism is overcome and cooperatives are strengthened [43,51]. By incorporating these considerations, bioelectricity in Ngwéi can become a potential model for a just and sustainable transition.

The results of this study demonstrate significant bioenergy potential. However, the existence of significant biomass potential does not, in itself, guarantee improved energy justice. A chain of technical, economic, institutional, and social conditions lies between the availability of the resource and households' actual access to affordable electricity [52]. In fact, beyond the theoretical potential analyzed in the study, the implementation of a bioenergy system in Ngwéi would depend on several other parameters not discussed here, including initial investment, the logistical organization of waste collection, facility maintenance, and the availability of stakeholders capable of ensuring long-term operation. Therefore, the study does not claim to demonstrate immediate feasibility but rather to identify a local energy resource that could serve as a basis for scenarios of gradual deployment. In this sense, these results alone would not be sufficient to guarantee a social and political transformation of energy access. Therefore, the hypothesis that utilizing oil palm biowaste would contribute to energy justice depends on institutional, economic, and organizational conditions, including the structuring of local supply chains, social acceptability, maintenance capacity, and coordination among stakeholders. In this sense, the quantitative results provide a basis for a technical feasibility study; translating these results into social benefits would require an appropriate governance framework.

5. Conclusions

This contribution aimed to explore the potential of valorizing biowaste from oil palm cultivation for a sustainable energy future in the Ngwei area of Cameroon. The methodology utilized data from secondary sources (grey literature) and primary sources (questionnaire surveys, focus groups). These data required statistical processing to extract the stock of usable biomass from oil palm plantations and, consequently, the energy potential that could be recovered through the valorization of this biomass. Simultaneously, the data analysis allowed for the estimation of greenhouse gas emissions that could be avoided in the area under a scenario involving the valorization of oil palm waste. The analysis demonstrates that valorizing biowaste from oil palm cultivation constitutes a potential alternative for equitable and sustainable access to electricity in the Ngwei Municipality. Investigations have revealed that Ngwéi is a rural municipality plagued by energy insecurity. Although crossed by two three-phase power lines (225 and 90 kV) leading to the country's capital, Yaoundé, the locality struggles to achieve optimal electrification from the national grid. This study assessed the theoretical potential for utilizing oil palm residues in the municipality of Ngwéi, based on field data and coefficients from the literature. The results indicate that the identified quantity of residues could represent a significant theoretical energy content. The municipality could theoretically generate, in addition to palm oil, approximately 207,593.603 MWh/year by recovering energy from the waste resulting from this production. However, this result does not constitute an estimate of the net electricity that could be generated or distributed to

households. Such an estimate would require local data on moisture content, conversion technology efficiency, equipment availability, auxiliary energy requirements, logistical losses, and distribution conditions. The study also highlights a theoretical emissions load associated with the scenario of uncontrolled residue decomposition. Recovering this waste, which is typically left in the environment, would theoretically prevent the emission of approximately 22,187.39 tCO_2e per year within the municipality. Recovering 90% of this waste would help address urgent challenges related to waste management, circular economy, and the promotion of sustainable energy. This value should not be interpreted as a net reduction in greenhouse gas emissions, as emissions related to collection, transport, drying, energy conversion, infrastructure, and methane leakage have not been quantified.

Exploring successful experiences, including community biogas systems in Kenya, cogeneration units in Indonesian palm groves, and Brazilian rural cooperatives, reveals that decentralized, locally managed energy production can significantly reduce inequalities in access to electricity, lessen pressure on forests, and sustainably boost the rural economy. These models are adaptable to Ngwéi if the following conditions are met: the development of a context conducive to the structured mobilization of oil palm residues at the local level; the establishment of a collaborative environment between cooperatives and agro-industrial actors in the oil palm sector; and the necessary institutional support to ensure the system's sustainability. Furthermore, new technologies like environmental recycling systems (ERS) have demonstrated efficiency in transforming the effluent and empty fruit bunch from the palm oil mill process into a solid biofuel, supporting circular economy goals. The emergence of these technologies demonstrates that there is a possibility to transform biowaste into sustainable energy through the process of valorization. This study shows that valorizing oil palm biowaste could be a credible option for improving energy access and reducing greenhouse gas emissions in the Ngwéi commune. However, this potential remains theoretical until certain parameters, such as collection, processing, financing, governance, and maintenance conditions, are met.

From the perspective of energy justice, the valorization of residues could offer an avenue for research and planning capable of contributing to a more equitable distribution of energy services. However, it does not, in itself, guarantee improvements in distributive, procedural, or recognition justice. Social outcomes would depend on infrastructure location, pricing structures, community participation, the representation of women and vulnerable groups, governance transparency, and the capacity to ensure the long-term maintenance of equipment. Consequently, the results should be viewed as an initial exploratory basis for a technical, economic, institutional, and environmental feasibility study. Prior to any implementation, the following would be required: local measurements of biomass and moisture content, residue characterization, a comparison of technologies, cost analysis, an assessment of energy needs, and a life-cycle analysis. The transferability of this approach to other rural areas in Cameroon or Africa cannot be established based on this study alone; it would require comparative research accounting for differences in resources, governance, production structures, financial capacities, and grid access conditions.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of interest

The authors declare no conflict of interest.

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