ASSESSMENT OF FORESTRY RESIDUES POTENTIAL FOR OFF-GRID ELECTRIFICATION IN THE REPUBLIC OF BENIN (WEST AFRICA)

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ABSTRACT

This study assessed the potential of forestry residues for off-grid electrification in the Republic of Benin while accounting for the spatial variation of residues potential and their use impact on local biodiversity. We found significant spatial variation of residues potential, with a much higher surplus residues in the north (3,599.05 tons/year) compared to the south (457.79 tons/year). This discrepancy might result from the spatial difference in geographical variables across the two regions. A maximum electricity potential of 100,259,786 kWh can be generated from the theoretical potential of residues which falls short of satisfying the estimated national off-grid electricity demand of 443,916,975 kWh. The research also highlighted the positive influence of wood processing technology and diversity of processed wood species on residues potential. The two variables may be targeted by policymakers to tailor actions for enhancing local transition towards renewable energy. Using scenarios-based projections, our study prompt the conclusion that forestry residues can be used sustainably for off-grid electrification with a minimal impact on biodiversity. Combining the surplus residues from wood processing industries with energy plantations may optimize forestry residues mobilization for off-grid electrification.

Keywords: *wood residues, biomass-electricity, off-grid power, sustainability*

INTRODUCTION

Biomass is the most abundant renewable carbon source that can be used to mitigate the environmental impacts of fossil resources [1]-[2]. Among biomass resources, forestry residues have gained substantial attention [3] and are considered more promising to reduce the environmental impacts of fossil resources compared to crop feedstocks [4]. Forestry residues include a spectrum of products, typically categorised into primary and secondary residues. Primary residues include stem wood, logging residues, and stumps resulting from forest operations, whereas secondary residues cover a spectrum of materials such as sawdust and cutter chips, bark, slabs, lump wood residues, and black liquor [5]-[6]. The most important component of secondary sources is wood processing residues, which comprise residues from sawmilling, residues from other wood processing activities, and black liquor [7]. Previous studies found that secondary sources of forestry residues tend to produce less impact on biodiversity than primary sources and even exhibit positive effects in some areas [8]-[9]. Additionally, studies have reported that logging residues used for energy purposes do not affect soil nutrient availability and provide additional environmental benefits such as the reduction of wildfire hazards and forest health improvement [10].

Forestry residues have gained prominence as a promising choice for electricity generation over the past two decades [11]-[13]. However, various factors may challenge the use of these feedstocks for energy purposes. Previous authors have provided important insight into the drivers of forestry residue availability for bioenergy. One of the main factors is the demand for sawlogs [14]. It was also reported that wood residues increase with wood production and depend on the type of industrial production (goal) and Roundwood conversion [15]. Wood residue availability may also be affected by the development of wood-based industries since the supply of wood for energy production strongly depends on this factor [16]. It may also be influenced by the forest or plantation management framework [17]. The availability of forestry residues for bioenergy can also be affected by natural disturbances, which, within a short period, might make a large amount of damaged and/or infected wood of poor quality unavailable to be used in the forest industries [18].

Various scholars also reported socioeconomic (competing activities) and biodiversity constraints as important drivers of forestry residue availability [17],[20]-[21]. Biodiversity considerations were also cited as a significant challenge in using forestry residue for energy

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production [9]. Another important, challenging factor is spatial disparities that may constrain the feasibility of biomass energy development. Spatial disparities encompass all forms of inequality in the distribution of geographical variables, such as income, economic opportunity, education, poverty, urbanisation, resource allocation, and more, across various geographical divisions [21]. The spatial structure of these variables may constrain residue availability through a complex spatial interdependence between various factors such as forest resources, socioeconomic development, commercial wood demand, etc.

At a regional scale, the assessment of forestry residues' potential for bioenergy has gained more attention from researchers in Europe [13],[23], the United States [14],[24], and Asia [24], with limited research efforts from Africa. Researchers in Africa are increasingly paying attention to agricultural residues [25], with poor research efforts about forestry residues, which thereby limit our understanding of the feasibility of using this type of biomass for energy purposes across the continent. The initial focus in bioenergy feasibility studies is the assessment of biomass potential. In theory, biomass potential assessment encompasses the assessment of various potential categories, including theoretical, technical, economical, sustainable, and sometimes implementation potential [26].

The theoretical potential is the overall maximum volume of biomass that is theoretically available for bioenergy production within fundamental biophysical limits and within a given time period [27]. The technical potential refers to the portion of the theoretical potential that can be realised within the existing technological capabilities and within the specific techno-structural framework conditions [28]. The economic potential represents the fraction of the technical potential that satisfies economic criteria [29]. The implementation potential is the subset of the economic potential that can be effectively put into practice within a given timeframe, taking into account various socio-political framework conditions, such as economic, institutional, and social limitations, as well as policy incentives [30]. This concept also encompasses the evaluation of the social, economic, and environmental impacts of bioenergy.

The concept of sustainable potential refers to the result of incorporating social, economic, and environmental, economic, and social sustainability criteria in biomass resource assessment [31]. The sustainable potential is also known as the surplus of biomass, which is the unutilised portion of the produced biomass after accounting for sustainability criteria [32]. The sustainability of biomass use for energy, therefore, requires consideration of several environmental, economic, and social factors to minimise adverse effects [33].

In the context of West Africa, such as Benin, the sustainable use of forestry residues for energy production would be hindered by residues allocation to meet socioeconomic demands (domestic energy, construction, and animal breeding), as well as the imperative for biodiversity conservation and land use change. These factors collectively define the sustainability criteria for the use of forestry residues in energy production.

The Republic of Benin is one of the West African countries that is strongly experiencing energy dependency, with a low coverage rate in rural areas (only 6.7%) and a high dependency on fossil fuels (50% of households) [34]-[36]. About 67% of the population is living off-grid while the country faces low production capacities in the face of increasing electricity demand [37]. Interestingly, Benin has considerable agricultural and forestry residues that can be harvested for electricity production [38]. Benin has embarked on various projects to develop renewable energies from solar, water, and residues from agriculture and forests [36]. Agricultural residue potential has received more consideration from bioenergy research in Benin [39]-[40], whereas forestry residues have received comparatively poor attention. This makes the government lack accurate data on forestry biomass potential, highlighting the need for biomass potential assessment to address this gap.

The main objective of this study is to assess forestry residues (sawdust, wood chips, and logging residues) potential for off-grid electrification in Benin. The study addressed the following questions:

1. What is the maximum quantity of forestry residues generated across the country and the subsequent surplus of residues available for energy? Is this maximum amount sufficient to meet the country's off-grid electricity demand?
2. In the future, can forestry residues be mobilised for the sustainable satisfaction of the country's off-grid electricity demand?

MATERIALS AND METHODS

Study Area

The study was carried out in the Republic of Benin, a West African country located between 6°15′ and 12°25′ N and 0°40′ and 3°45′E. The country covers an area of 114,763 km^2 with a population density of 87.2 inhabitants per km^2 (11,186,785 inhabitants) in 2017 [41]. The rainfall varies from 800 mm in the Sudanese zone (North) to 1,300 mm in the Guinean zone (south) [36]-[37]. Soils are ferruginous in the North and ferralitic in the South. The vegetation is mainly composed of savannas. Benin exhibits some spatial disparities considering forest cover, socioeconomic traits, and energy constraints. The North is more evergreen and is more covered with natural forests, representing 92.5% of the country's forest cover [38]. Natural forests are the main source of woody biomass in the North, whereas teak (Tectona grandis) and acacia tree (Acacia auriculiformis) plantations are the main woody biomass sources in the South. The South is more populated (57.60 inhabitants per km^2) compared to the North (29.59 inhabitants per km^2).

About 42% of the population of Benin is poor, with a higher rate of poverty in the North (60.07% of the population) compared to the South (35% of the population). Approximately half of the country's households (50%) used fossil fuel for lighting, with a higher rate in the South (59.22%) compared to the North (20.82%). About a third of the country's households (33.42%) purchase electricity from the government [35], with a far higher access rate (34.55% of the households) in the South than in the North (18.52%) [36]. Energy sources, such as solar power and residue-derived energy (from forestry and agriculture), are limitedly used across the country. Like many West African countries, Benin highly depends on external energy, with 100% of fossil fuels and 90% of power imported from Nigeria and Ghana [36]. Yet, only 6.7% of rural households have access to electricity [36], although an important amount of crops and forestry residues may be collected for electricity production. The survey area covered six localities and five short-rotation plantations in the Republic of Benin (Figure 1).

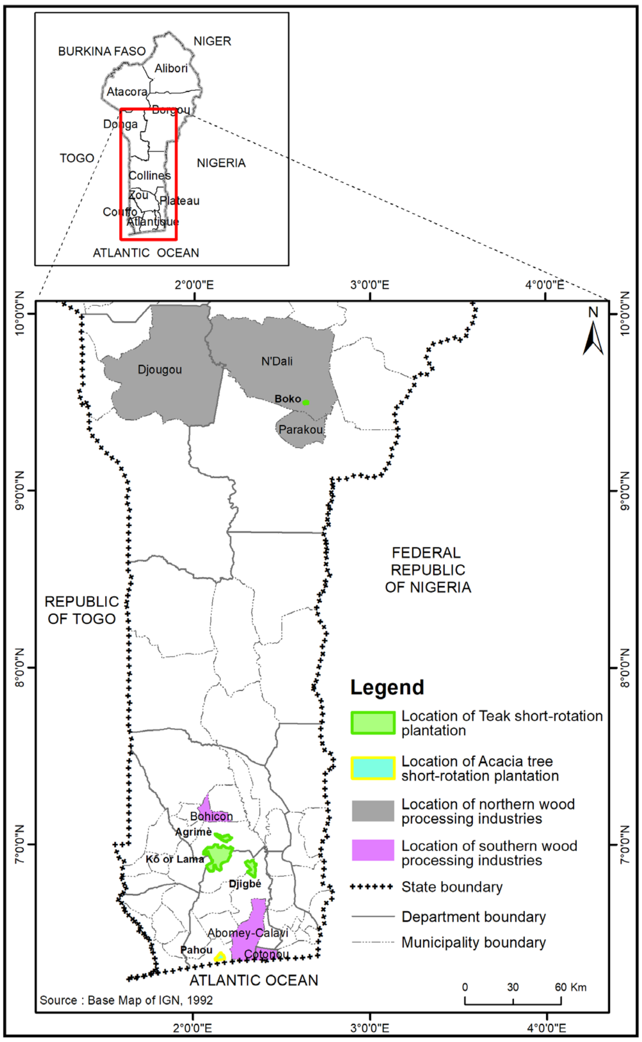

Figure 1 Study area showing the geographical locations of wood processing industries and short-rotation plantations

The General Approach Used for Biomass Assessment

A general approach that encompasses five stages were used, as described in a previous study [28]:

1. The sustainability criteria and other constraints that constrain the residues' availability were identified. Based on these criteria, we estimated the amount of residues used for socioeconomic needs.
2. The net available residue potential (surplus) was estimated based on the identified sustainability criteria.
3. The moisture content of the residues was calculated, and subsequent electricity potential was estimated from the theoretical potential and surplus of residues. At this stage, we employed the methodology developed by Vis et al. [26], Batidzirai et al. [28], and Saal et al. [15].
4. A scenarios-based projection approach was used to assess the potential of forestry residues in meeting sustainable future off-grid electricity [46].

Sampling and Biomass Measurement

Measurements of Wood Processing Residues (WPR)

A random sample of 136 wood processing industries (WPI) was surveyed, and the following information was recorded: the maximum daily average volume of logs processed, the type of final manufactured product, the diversity of wood processing technologies (technological level), and the number of wood species processed. Afterwards, the biomass measurements were conducted based on the material flow analysis approach to make accurate estimations [15].

The measurement was conducted following the material processing steps, beginning with the initial wood volume input and concluding with the final product output. At each material processing step, the input volume of wood was measured. For each final manufactured product, the accumulation of sawdust and wood chips was quantified through all conversion steps from an input volume of logs or planks. A 50 kg capacity spring balance was used with a precision of ±0.05 kg to make these measurements. Additionally, the quantities of sawdust and wood chips sold at each WPI location were measured. In estimating the dry potential of residues, the moisture content of each type of residue was calculated by oven-drying fresh samples. This process involved oven-drying 0.10 kg of wood chips and 0.25 kg of sawdust for 72 hours at the "Laboratoire de Phytopathologie et Protection des Végétaux" at the University of Parakou.

Measurements of Short-Rotation Plantations Residues (SRPR)

40 square plots of 100 m^{-2} size (20 for teak and 20 for Acacia tree) were randomly installed in five short-rotation plantations with a 6-year growth period (Figure 1). In each plot, all the trees were systematically felled, using local tools and with the assistance of plantation managers. Immediately following the felling process, the harvested tree biomass was categorised into two main groups: commercial wood, which is intended for sale and use in fuel or construction, and non-commercial wood, typically consisting of small branches and leaves. The tiny branches into portions were separated, distinguishing those used by households for cooking and the unused biomass, allowing us to assess the surplus of residues. For quantifying the weight of the tiny branches, a 50 kg capacity spring balance was used with a precision of ±0.05 kg. The tiny branches were grouped into bundles that matched the capacity of the scale and subsequently weighed. In determining the moisture content of the wood residues, 0.50 kg samples of fresh biomass were collected for each tree species (teak and Acacia). These samples were then subjected to a 72-hour oven-drying process at the "Laboratoire de Phytopathologie et Protection des Végétaux" at the University of Parakou.

Estimation of Fresh and Dry WPR Potential

Fresh WPR Potential Estimation

For each surveyed WPI, the fresh theoretical potential of WPR was estimated using equation suggested by Vis et al. [26] as:

$$fThWPR_t = \sum_{i=1}^{n} fThWPR_{ti} \quad (1)$$

where, $fThWPR_t$ represents the fresh theoretical potential of type t residue, $fThWPR_{ti}$ is the fresh theoretical potential of type t residue for the manufactured i product, and n represents the number of manufactured products. The $fThWPR_{ti}$ was estimated on the following equation:

$$fThWPR_{ti} = \sum_{j=1}^{n} Q_{tij} \quad (2)$$

where, Q_{tij} is the fresh weight of type t residue for the manufactured i product at j wood processing step.

The $fThWPR_t$ values and the sustainability criteria were used to estimate the fresh weight of residues surplus for each WPI using the equation suggested Vis et al. [26].

$$fThWPR_t = fThWPR_t - U_t \quad (3)$$

where $fThWPR_t$ is the surplus of type t residue and U_t represents the fresh weight of type t residue harvested for different competition uses.

Dry WPR Potential Estimation

The dry potential of WPR was determined based on the dry mass basis moisture content of each type of residue. The moisture content values for wood chips and sawdust were 30% and 28%, respectively, after oven-drying the residue samples at the Laboratory.

For each WPI, the dry theoretical potential and surplus for the pooled types of residue were determined using the following equation.

$$dP = \sum_{t=1}^{n} \frac{fP_t}{(1+M_{tdb})} \quad (4)$$

where dP is the dry theoretical potential or the dry surplus of residues, fP_t is the fresh theoretical potential of residues or fresh surplus of residues Equations 1 and 3, and M_{tdb} the dry mass basis moisture content of type t residue.

Based on dP, the dry region-specific potential and national potential were determined using the equation below:

$$DP = \sum_{1}^{n,N} dP \quad (5)$$

where DP is the region-specific or country-scale dry theoretical potential or dry surplus of residues, n is the number of surveyed WPI in each region, and N is the total number of WPI surveyed across the country.

Estimation of Fresh and Dry SRPR Potential

Fresh SRPR Potential Estimation

The fresh theoretical potential or surplus of SRPR was estimated as:

$$fSRPR = \sum_{i=1}^{n} \mathrm{HA_i} \times \left(\frac{Q_i}{0.01ha} \right) \quad (6)$$

where $fSRPR$ is the fresh theoretical potential or surplus of residues at the country or regional scale, Q_i is the mean fresh theoretical potential or surplus of residues for i species within the sampled 100 m^2 plot, HA_i is the mean annual harvested plantation area (ha) for i species. HA values were obtained from the National Forest Office report [47]. The HA=612.44 ha for teak and 544.53 ha for Acacia trees were used.

Dry SRPR potential estimation

Based on the fresh SRPR potential, the dry theoretical potential or surplus was determined using the dry basis moisture content value of 14% for teak and 12% for Acacia trees after wood samples were oven-dried at the Laboratory.

Electricity Potential of WPR and SRPR

The theoretical quantity of electricity from the residues was determined based on the dry potential of residues and the net calorific value by using Equation 7, as recommended by FAO [48].

$$BP = DP \times NCV \times c \quad (7)$$

where BP, is the region-specific or country-scale electricity potential, *DP* is the total dry surplus or theoretical potential of residues, which was obtained by cumulating WPR and SRPR dry potentials.

NCV is the net calorific value, and c represents a conversion factor. In this study, NCV=18.5 MJ/kg and c=1/3600 as recommended by FAO [48].

After *BP* determination, we evaluated the contribution of *BP* to the national off-grid electricity demand using the following equation:

$$CP\ (\%) = 100 \times \frac{\mathrm{BP}}{\mathrm{ED}} \quad (8)$$

where *CP* is the contribution of *BP* to the national off-grid electricity demand, and *ED* represents the region-specific or the national off-grid electricity demand which was estimated using the following equation:

$$ED = AC \times \left(\mathrm{PS} - \frac{\mathrm{PS} \times \mathrm{r}}{100} \right) \quad (9)$$

where PS is the current number of people living off-grid, r is the region-specific or country-scale electricity access rate, and AC represents the mean annual electricity consumption per capita, which was calculated based on the World Bank data from 1980 to 2021. The electricity access rate was obtained from the 2020 national report on electricity status [34].

Factors Influencing the Availability of Forestry Residues

We first performed two candidate models, including linear mixed effect models using the lme4 package [49] and the Generalized Least Squares model. For the two models, we used as response variables the dry theoretical potential or surplus of residues, and as explanatory variables, the geographical region (north and south), the type of manufactured product (pallets and cover plates), the number of processed wood species, and the processing technological level of the industry. The geographical region was used as a random factor in the linear mixed effects model. We selected the appropriate model based on Akaike's Information Criterion. The appropriate model should minimise the AIC value, and models showing $\Delta AIC(AIC_i - AIC_{min})$ value less than two are expected to have similar support for being the best models [50]. AIC_i is the AIC value for a given model while AIC_{min} is the smallest AIC value.

Future Use of Forestry Residues for Off-Grid Electrification and its Impact on Biodiversity

The scenarios-based projection approach [46] was performed using existing statistical data and off-grid population density scenarios in the literature. Specifically, these scenarios were used to predict the following variables:

1. The necessary quantity of forestry residues is required to meet the national off-grid electricity demand.
2. The necessary land area is required to generate the required amount of residues from acacia trees and teak energy plantations.
3. Biodiversity impact index.

The three variables above were predicted based on the following scenarios:

1. Scenario 2023: 73035.6 persons.km^{-2} are currently living off-grid in the Republic of Benin.
2. Scenario 2028: 20354 persons.km^{-2} will be off-grid by 2028, regardless of government efforts.
3. Scenario 2030: 15044 persons.km^{-2} will be off-grid by 2030, regardless of government efforts.

The last two scenarios (scenario 2028 and scenario 2030) were predicted by MCA Benin II [51], and the first (scenario 2023) was defined based on existing data on electricity access rates in the Benin Republic [34].

Scenarios-driven Supply Potential of Forestry Residues

The necessary quantity of residues required to meet off-grid electricity demand was estimated using the demand-driven approach based on the equation as:

$$RS_i = ED_i \times \frac{E}{NCV} \quad (10)$$

where RS_i represents the required quantity of residues supply to meet off-grid electricity demand under i scenario, ED_i is off-grid electricity demand under i scenario, E is the energy conversion factor, which is the KJ equivalence of kWh. E=3,600, and NCV is the net calorific value. NCV=18.5MJ.Kg^{-1}

Impact of Scenarios-Driven Supply Potential on Biodiversity

To assess scenarios-based projections' impact on biodiversity, we used the biodiversity impact index, the ratio of scenarios-related land area (LA_i) to the national surplus of cultivable land area as defined by the following equation:

$$BI_i = \frac{LA_i}{A_i} \quad (11)$$

where BI_i is the biodiversity impact index, LA_i is the required land area for satisfying off-grid electricity demand under i scenario, and A_i is the surplus of cultivable land area in the country under i scenario. A_i were extracted from the Ministry of Agriculture report [52]. The impact is assessed to be negative when $BI_i > 1$ and positive when $BI_i < 1$. LA_i was calculated using the following equation.

$$LA_i = \frac{RS_i}{y_i \times \rho} \quad (12)$$

where y_i is the productivity of short-rotation plantation for i species, and ρ represents wood bulk density. In this study, r_i=72 m^{-3}. ha^{-1} for acacia tree plantation [49]-[50]. For teak plantation, r_i=90m^{-3}.ha^{-1} [55]. ρ = 460 kg.m^{-3} [48].

RESULTS

Theoretical Potential of Forestry Residues and Available Surplus for Energy

In terms of WPR, the theoretical potential in the North and south regions exhibited no significant difference (Table 1). However, the North had a higher surplus of WPR compared to the South, with 40.38% of the theoretical potential available as surplus in the North, whereas the South had 5.54%. When WPR and SRPR potential are combined, we observed a greater surplus in the North (40.22%) compared to the South (9.33%). However, the theoretical potential between the two regions remained similar, with 9,681 tons of dry weight in the North and 9,829 tons in the South annually. Combining data from both regions, the national-scale theoretical potential was estimated at 19,510.01 tons annually, with approximately 25% of this potential available as surplus. In contrast to WPR, we found a slightly higher theoretical potential of SRPR in the South, but the surplus was similar between the two regions. The North generates approximately 916.05 tons of SRPR annually, while the South produces 1,417.62 tons. This results in approximately 32% of the theoretical potential being available as surplus in both regions. On a national scale, the potential for SRPR is smaller than that of WPR, with an annual production of 2,333.67 tons. Approximately 32% of this potential is available as surplus.

Table 1 Cross-national and region-specific potential of forestry residues

	WPR		SRPR		Total	
Region	ThP	SP (%ThP)	ThP	SP (%ThP)	ThP	SP (%ThP)
North	8,912.96	40.38	916.05	32.08	9,681	40.22
South	8,263.38	5.54	1,417.62	32.38	9,829.01	9.33
Total	17,176.34	23.62	2,333.67	32.27	19,510.01	24.66

Legend: ThP = Theoretical potential, SP = Surplus potential, WPR = Wood processing residues, SRPR = Short-Rotation Plantation Residues. ThP was measured in tons per year (tons/year).

Electricity Potential from Forestry Residues

Currently, the off-grid electricity demand significantly exceeds the available electricity potential supply from forestry residues, both at the national level and within different geographical regions. The current theoretical and surplus residues can only fulfil 22.59% and

Table 2 Cross-national and region-specific bioenergy potential of forestry residues

	SP		ThP	CP		PD	
Region	ED (kWh)	BP (kWh)	BP (kWh)	SP	ThP	PD/SP	PD/ThP
North	284,372,116	20,006,867	50,510,185.6	7.04	17.76	3,084.91	7,788.3
South	159,544,859	4,712,443.71	49,749,600.6	2.95	31.18	726.62	7,671.02
Total	443,916,975	24,719,310.8	100,259,786	5.57	22.59	3,811.54	15,459.32

Legend: ThP =Theoretical potential, SP = Surplus potential, ED = Off-grid energy demand, BP = Bioenergy potential, PD = population density, CP = Contribution of the surplus or theoretical potential to off-grid energy demand, kWh = kilowatt-hour.

Table 3 Results from the Generalized Least Squares model showing the factors that influence forestry residue availability

	ThP				SP			
	β	se	t.value	p	β	se	t. value	p
(Intercept)	3.276	0.185	17.740	0.000***	181.685	81.97	2.21	0.03*
Technological Level	0.082	0.018	4.514	0.000***	2.592	9.37	0.27	0.78ns
NPS	0.176	0.028	6.208	0.000***	-1.324	11.51	-0.11	0.91ns
Pallets (Cover plate)	-0.002	0.132	-0.012	0.991ns	49.782	44.16	1.12	0.262ns
South (North)	-0.029	0.116	-2.843	0.555ns	-192.79	39.76	-4.84	0.000***

Legend: ThP = Theoretical potential, SP = Surplus potential, β = Regression coefficient, se = standard error, P = probability value, modality within the bracket is the reference for comparison. NPS = Number of processed wood species. Terms in parentheses are the baseline modality for comparison. ThP was log-transformed to meet the normality assumption. *** p < 0.001, ** p < 0.01, and ns indicates non-significant p-values.

5.57%, respectively, of the national off-grid electricity demand (as outlined in Table 2). When we examined the spatial distribution of the supply, we found that only 2.95% of the off-grid demand can be satisfied by the surplus residues in the South, in contrast to 7.04% in the North. In the South, approximately 17.76% of the off-grid demand can be met by the region's theoretical potential, while the North can cover 31.18% of its demand using its theoretical potential. In terms of energy access potential, the current national theoretical potential can provide electricity to a population density of 15,459.32 inhabitants.km^{-2}. This energy access potential is similar between the North and South regions, where approximately 7,788.30 inhabitants.km^{-2} in the North and 7,671.02 inhabitants.km^{-2} in the South can be electrified using the theoretical potential. When we consider the surplus potential, it can electrify 3,811.54 inhabitants.km^{-2} at the national scale, with 3,084.91 inhabitants.km^{-2} in the North and 726.62 inhabitants.km^{-2} in the South benefiting from this surplus.

Factors Influencing the Production and Availability of Forestry Residues

The theoretical potential was significantly influenced by the technological level of wood processing industries and the number of processed species (Table 3). The potential increased with the number of processed species (β = 0.176±0.028; p = 0.000) and technological level (β = 0.082±0.018; p = 0.000). Only the geographical region exhibited a significant effect on the residues surplus, showing significantly lower surplus potential in the South compared to the South (β = -192.793±39.769; p = 0.000).

Future Supply of Forestry Residues and Biodiversity Impacts

Based on scenario 2023, the off-grid electricity demand was estimated at 443,916,974.50 kWh.year^{-1} (Table 4). To meet this demand, 86,383.84 dry tons.year^{-1} of forestry residues would be required. However, projections for 2028 and 2030 anticipate a decline in off-grid electricity demand due to reduced off-grid population density. Scenario 2028 projected off-grid electricity demand to be 132,003,571.43 kWh.year^{-1}, requiring 25,687.18 tons.year^{-1} of dry residues. By 2030, off-grid electricity demand is projected to be 97,567,857.14 kWh.year^{-1}, necessitating 18,986.18 tons.year^{-1} of dry residues. These projections reveal that the land area required to produce the necessary residues is significantly smaller than the national surplus of cultivable land area. The Biodiversity Impact (BI) index values were low, ranging from 2.42% to 5.92%. These values indicate that using forestry residues from energy plantations to meet off-grid electricity demand will have minimal impact on biodiversity.

Table 4 Scenario-based projection of forestry residues supply for off-grid electrification and its impact on biodiversity

	Scenarios		
	2023	2028	2030
Population density (persons.km^{-2})	73,035.65	20,353.98	15044.25
Off-grid electricity demand (kWh.year^{-1})	443,916,974.50	132,003,571.43	97,567,857.14
RS_i (ton year^{-1})	86,383.84	25,687.18	18,986.18
LA_i for Acacia	152,304.41	45,289.38	33,474.77
LA_i for Teak	227,927.95	67,776.87	50,095.96
A_i	3,850,355.06	1,868,532.56	1,302,297.56
BI for Acacia (%)	3.96	2.42	2.57
BI for Teak (%)	5.92	3.63	3.85

Legend: RS_i =Required amount of residues to meet off-grid electricity demand under i scenario, LA_i=Required land area to produce the required amount of residues under i scebario, A_i=Surplus of cultivable land area in the country under i scenario, BI= Index of scenario-based projections' impact on local biodiversity calculated as LA_i devided by A_i. A_i values are extracted from the Ministry of Agriculture report [52].

CONCLUSION

This study assessed forestry residue potential for off-grid electrification in the Republic of Benin while accounting for spatial variation of the residue potential and biodiversity significance. Our results revealed that the country has a high potential for forestry residues, but only a quarter (25%) of this potential can be harvested for energy production due to the high competition from other uses. Additionally, significant spatial variation in the residues potential was found with a much greater surplus in the North (40.22%) compared to the South (9.33%), which might result from the spatial differences in socioeconomic variables between the two regions. This finding prompts two important conclusions. The first is that the use of forestry residues for off-grid electrification would be more feasible in the northern region. Secondly, it underlines the need to enhance people's intentions to supply the residues for energy production in the South. Our results show that only 22.59% of the current off-grid electricity demand can be met with the energy potential from the national residues potential, suggesting the need to develop energy plantations. Scenarios-based projections indicate that growing energy plantations for off-grid electrification can be achieved sustainably given that future supply of land area for energy plantations would not affect forest land and represents a small fraction (2 to 6%) of the national surplus of cultivable land area. This option can be optimized by combining the surplus of wood processing residues with energy plantation potential. The diversity of processed wood species and the technological performance of industries have positively influenced forestry residues potential. This suggests that promoting forest conservation and enhancing wood processing technology would help optimize residues mobilization for off-grid electrification.

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