Bioenergy and Electric Power Generation from Agricultural Residues in Morocco: Lessons for Brazil

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***Abstract*—Brazil's and Morocco's energy sectors face a persistent challenge in their heavy reliance on fossil fuel consumption. Brazil is a big consumer of liquefied natural gas (LNG), while Morocco is a big fossil fuel importer. This dependence not only entails substantial import costs for Morocco and high NG liquefaction and transportation expenses for Brazil, but also contributes to elevated carbon emissions. Consequently, Brazil and Morocco are actively exploring substitute resources of renewable power to decrease their dependence on natural fuels and align with global renewable energy targets, including those set forth in agreements like the Kyoto Protocol. Brazil and Morocco boast an abundant array of renewable energy resources, including wind, hydro, solar, and biomass. Leveraging these resources has the potential to swiftly propel these countries towards a low-carbon emissions status when harnessed sustainably for electric power generation. Instead of relying on fossil fuels, the focus of this study is on tapping into the significant potential for power and electricity generation from agricultural residues in Morocco, giving the lessons to Brazilian energy sector for power and electric energy generation form ample agricultural biomass within Brazil. The results show a high potential for energy and electricity generation from cereals, olive biomass, citrus, and date palm residues in Morocco, while cereals, citrus, and sugarcane have better potential for bioenergy and electricity generation in Brazil.**

Link to graphical and video abstracts, and to code: https://latamt.ieeer9.org/index.php/transactions/article/view/9186

***Index Terms*—Agricultural biomass, bioelectricity, clean energy generation, electric power.**

I. Introduction

Brazil and Morocco present a vast array of opportunities for diverse renewable energy sources, encompassing biomass, solar, hydro, and wind power [1]. These resources have the potential to significantly contribute to meeting the major part of energy needs of 217.7 million habitants in Brazil and Morocco's current population of 36 million [2], [3]. While hydroelectric power remains the predominant sustainable energy source in several nations, with Brazil and Morocco inclusive, there is a discernible declining trend in its share of universal power generation mix because of global warming to meet the growing worldwide energy demand as a result of population growth and industrialization. Morocco and Brazil are no exception to this trend, as illustrated in Figs. 1 to 3 [4], [5].

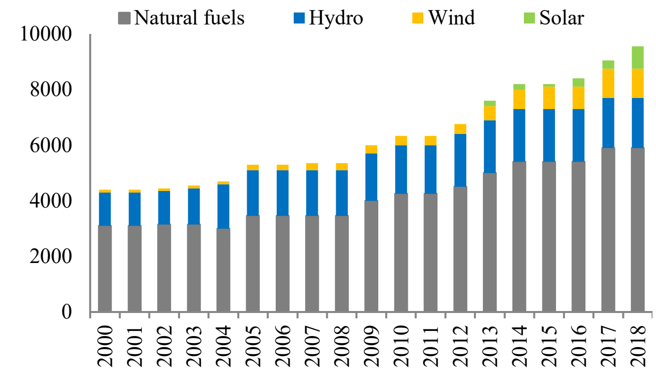

Fig. 1. The power generation capacity in Morocco from 2000 to 2018.

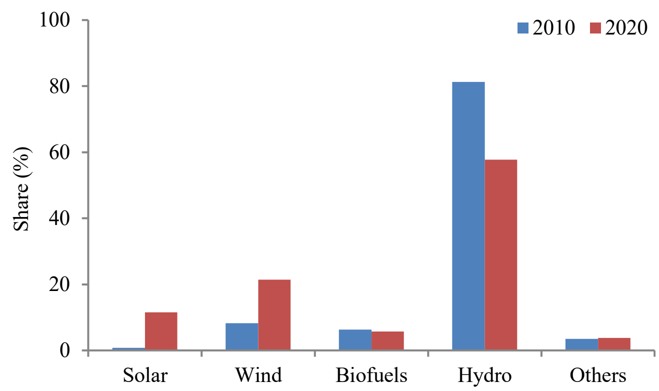

Fig. 2. The share of renewable sources in the global clean energy generation.

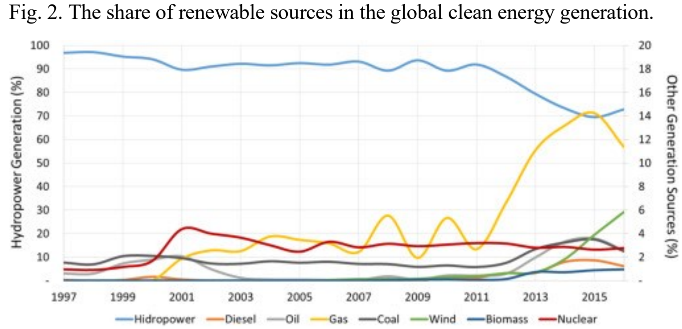

Fig. 3. Electricity generation in Brazil by energy source [5].

Aside the growing energy demand and rapid industrialization which has resulted in the usage of fossil to meet energy demand, the reduction in global water levels has also contributed to the decrease in the share of hydroelectric power in global electricity generation mix. This decline water level can be attributed to the impact of global warming, which has led to decreased natural precipitation levels, resulting in more frequent droughts and a reduction in the water head available for hydroelectric sources. Given Morocco's and Brazil's persistent drought challenges, alternative renewable

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sources such as solar, wind, and biomass energy have emerged as viable options for these nations' long-term energy sustainability [6], [7]. These sources can be instrumental in enabling Brazil and Morocco to align with global agreements, e.g. Paris Agreement, which strives to limit the increase in global temperatures to less than 1.5°C compared to before the industrial revolution era [8]. However, reliance of wind and photovoltaic (PV) systems on weather elements such as sun radiation flux and wind velocity presents a challenge when assessing the security and reliability of their power supply, as highlighted in [9] and [10]. To address the issue of power supply instability stemming from the intermittent nature of wind and PV generation, exploring power from biomass sources, e.g. agriculture leftovers emerges as a promising way. This approach can offer a reliable source of energy to final consumers during periods that solar and wind energies may be unavailable, as discussed in [11]. Agricultural biomass holds a pivotal role as a vital global renewable resource, capable of serving as a significant contributor in combating global warming, as emphasized in [12]. Harnessing this resource for energy generation, as detailed in [13], has the potential to become even more impactful local inhabitants through local job creation. This prospect is set to expand further due to the escalating demand for food driven by population growth, as noted in [14]. It is crucial to highlight that when employing agricultural biomass for energy generation, careful consideration must be given to avoid conflicting with farmlands allocated for producing food crops and lands for producing energy crops [15].

In addition to the issue of land allocation, another noteworthy challenge arises from the substantial water requirements for cultivating energy crops at areas with short-lived natural precipitation where irrigation is indispensable. This demand for water can potentially impede the availability of this vital resource for irrigating food crops, as outlined in [16]. The North Africa and Middle East (MENA) nations, which include Morocco, as well as North of Brazil represent some of the most water-scarce districts worldwide. The demand for water resources in these regions is expected to escalate due to population growth, urbanization, the effects of climate change, and the surging demand for agricultural and food production, as indicated in [17]. In this context, agricultural residues (agricultural leftovers) offer a potential solution to the challenge of land and water competition betwixt eatable and energy crops. Unlike energy crops, remnants from agriculture will not necessitate dedicated water and land for cultivation, as they are derived from the remnants of food crop production, as elaborated in [18]. Agricultural biomass comprises all biodegradable, non-fossilized organic materials derived from both plant and animal sources [11]. Globally, biowastes stands as the 4th major origins of power, trailing behind natural gas, oil, and coal [19]. Figs. 4 and 5 highlight Africa's and Brazil's significant reliance on renewable energy to fulfill their energy requirements. However, the 8.31% of bioelectricity generation in Brazil and Fig. 6 reveal that the generation of electric power from biomass resources remains relatively low in these two countries [20].

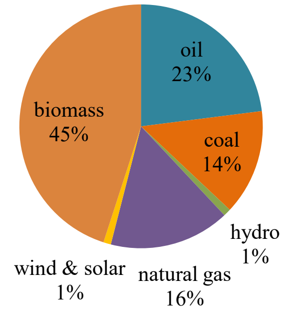

Fig. 4. The distribution of energy demand across various sources in Africa, represented as percentages.

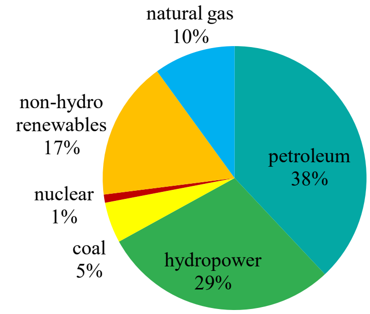

Fig. 5. Total primary energy consumption of Brazil.

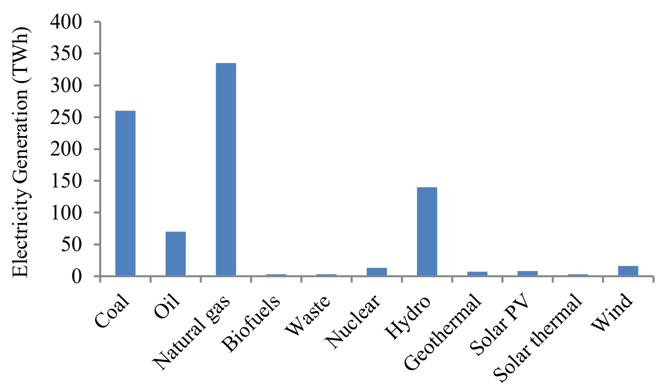

Fig. 6. The allocation of electric power production from diverse sources in Africa, presented in terms of their respective shares.

Utilizing plant wastes for energy generation, as discussed in [21], offers a dual advantage. Firstly, it doesn't adversely affect food crop production, safeguarding agricultural resources. Secondly, it diminishes the nation's reliance on fossil fuels, thereby curbing CO_2 emissions. Additionally, it addresses the challenges posed by the irregular essence of solar and wind power usage. Furthermore, the fact that agri-biomasses do not require additional water or land resources enhances their suitability for power generation, as indicated in [22]. Opting to utilize farm leftovers for energy requirements can also serve as a solution to the open-field burning of residues during land preparation. This can lead to significant reductions in both greenhouse gas (GHG) emissions and air pollution, as underscored in [23]. This poses a significant health hazard to both individuals and the environment, particularly in regions like Morocco and North of Brazil where dry seasons tend to extend beyond normal durations [24]. In addition to the issues stemming from the open combustion of crop residues, the widespread reliance on agricultural biomass as the primary cooking fuel in Africa poses significant health risks. Moreover, it diminishes the valuable moments available to children and women for productive work, as they are often engaged in gathering these residues for fuel. Nonetheless, crop residues have the potential to function as carbon sinks when employed for energy generation if the appropriate conversion technologies are utilized, as elucidated in [25].

Brazil's and Morocco's agricultural sectors hold the distinction of being the foremost consumer of water resources, comprising nearly seven- and nine-tenth of the countries' aggregate water consumption, respectively, as highlighted in [26] and [27]. The agricultural sector makes a significant contribution to the national economy, constituting approximately 20% and 6% of Morocco's and Brazil's Gross Domestic Product (GDP), respectively. Moreover, it plays a pivotal role in the labor market, employing 43% of the national workforce and a substantial 78% of rural jobs. Despite its substantial potential in agriculture, the Moroccan agricultural sector exhibits relatively modest energy consumption, accounting for just 7% of the overall energy usage, as indicated in [28]. Morocco boasts an extensive 68% coverage of arable land, with a notable 80% of this arable expanse situated in semi-dry and arid regions. Morocco experiences relatively modest annual precipitation levels, with averages ranging from 800 mm in the western regions to as low as 100 mm in the southern parts, as detailed in reference [29]. As a result, mechanized irrigation in agriculture becomes imperative for sustaining the food needs of the population. Furthermore, harnessing energy from crop residues has the potential to bolster the country's agriculture sector.

Morocco's and Brazil's potential for producing electricity via farming wastes is unquestionable, given these nations' substantial agricultural output and the vast quantity of residues available from agricultural practices such as crop pruning and the utilization of inedible crop parts, as elucidated in references [30]. However, available data reveals that Morocco and Brazil tap into merely 2% and 8% of their total biological material for energy, respectively. Leveraging biomass for generating energy is strongly endorsed in these countries, particularly when taking into consideration the significant intermittency and initial costs related to wind and solar energy utilization [31], [32], along with the transmission and distribution challenges [33]-[35] faced in delivering this energy to final customers. One more advantage of generating energy from biomass is the potential to bridge the gap between rural and urban advances by fostering regional occupation opportunities and providing social services accessibility. Often, these facilities are primarily available in cities owing to their reliance on consistent access to electric power, as highlighted in [36]. To date, numerous research studies have delved into harnessing power from framing leftovers in diverse territories. These investigations span a wide global landscape, encompassing nations like Jordan [37], Iraq [38], Turkey [39], Saudi Arabia [40], Argentina [41], China [42], India [43], Greece [44], Italy [45], Ukraine [46], Pakistan [47], Colombia [48], Malaysia [49], Indonesia [49], Thailand [49], Bangladesh [50], and South Korea [51]. Nonetheless, the quantity of electric power and electricity derived from crop waste has not been investigated in Morocco by all studies mentioned above. It is should be mentioned that studying potential of energy generation from agricultural residues in Morocco produces different results because the bioenergy contingent upon various factors, including the extent of cultivated land, crop yields, the ratio of crop residues to the total crop output, the efficiency of crop residue recovery, and the energy content inherent in these residues, among several other variables. Furthermore, it is important to note that these parameters are influenced by geographical location and the specific crop species being cultivated. Also, none of studies above has estimated the energy output from agri-biomasses in Morocco and compared the results with bioenergy potential of the biggest producers of agricultural products worldwide, Brazil. This comparison assumes vital importance, as it will provide essential recommendations for the Brazilian policymakers and governments when determining the most judicious power outlay decisions. In line with this aim, main novelties and contribution of the current paper are:

- Estimating gross energy generation and electric power potential of key agricultural residues such as peanut, sugarcane, sunflower, market gardening plants, citrus, and cereal biomass in Morocco and Brazil.
- Providing important recommendations and information for the Brazilian energy sector based on Morocco's experience in sustainable power and electricity generation.
- Derivation of important lessons for Brazil by assessing the feasibility and potential of generating energy and bioelectricity from crop residues in Morocco.

Therefore, the main objective of the current research is calculating the biomass potential of key agricultural crops in Morocco and using the Morocco's experience to estimate the potential of bioelectricity generation from such products in Brazil.

II. Calculations for Energy and Power

Farm leftovers, owing to substantial energy content, serve as viable fuel sources for both heating and electricity generation. This can be achieved through various energy conversion techniques encompassing biochemical, biological, and thermochemical technologies [52]. In particular, the thermochemical approach involves residues combustion, a prevalent method to extract the biomass's energy. This energy (T_i), derived from crop type *i*, may be quantified using equation (1) [53].

$$H_i = T_i - HL_i \tag{1}$$

In Equation (1), HL_i represents the aggregate energy losses attributable to factors like uncompleted combustion, combustor's heat loss, biomass's water, as well as gas emissions. It is noteworthy that a segment of biomass is utilized during the combustion process for the purpose of evaporating the moisture contained within the biomass. Furthermore, T_i represents the theoretical heat energy potential (in MJ) that can be derived from crop type *i*. This value is computable as follows:

$$T_i = 10^3 \times M_i \times HHV_i \tag{2}$$

Here, M_i stands for the quantity of dry biomass (in tons), and HHV_i signifies the higher heating value (HHV) of crop type *i* (in MJ/kg). The mass of dry agricultural residues can be determined using equation (3) [53].

$$M_i = Y_i \times A_i \tag{3}$$

In equation (3), A_i and Y_i correspond to the cultivated land size (in hectares) and the residue yield of biomass type *i* (measured in t/ha). In specialized literature, various methodologies have been introduced for calculating the HHV, utilizing both evolutionary and traditional techniques. In a particular study in [54], the HHV of crop residues is expressed in relation to its carbon content (C_i), hydrogen content (H_i), and nitrogen content (N_i), with the following representation.

$$HHV_i = 1870C_i^2 - 144000C_i - 2820000H_i + 63800C_iH_i + 129000N_i + 20147000 \tag{4}$$

$$HHV_i = 5220C_i^2 - 319000C_i - 1647000H_i + 38600C_iH_i + 133000N_i + 21028000 \tag{5}$$

In the context of determining agri-biomass's HHV, this study opts to utilize the average of equations (5) and (6), denoted as equation (7) [54].

$$HHV_i = 3550C_i^2 - 232000C_i - 2230000H_i + 51200C_iH_i + 131000N_i + 20600000 \tag{7}$$

The HHV serves as a crucial metric for gauging the energy generation potential of agricultural biomass. However, it is noteworthy that even after drying, crop residues may retain some residual moisture content. This water diminishes HHV amount and entails the utilization of a portion of the residue's energy for evaporating the moisture. To account for this moisture effect in heating value calculations, the lower value of heat (LHV) is employed. The LHV of biomass can be determined using equation (8) [55].

$$LHV_i = HHV_i\left(\frac{100-\alpha_i}{100}\right) - 2.443\frac{\alpha_i}{100} \tag{8}$$

Within equation (8), α_i represents the moisture content expressed as a percentage. Consequently, equation (2) can be reformulated in the following manner.

$$T_i = 10^3 \times M_i \times LHV_i \tag{9}$$

By defining Av_i as the usability of *i*th residue for generating energy, we establish the following relationship:

$$Av_i = \frac{T_i - HL_i}{T_i} \tag{10}$$

Usability depends on moisture, incomplete combustion, and combustor heat loss. Water makes up a significant part of biomass and evaporates during combustion, greatly reducing the biomass volume for energy production. Each crop residue has specific usable energy after water removal. Biomass with lower moisture indicates higher usability and greater energy yield, as shown in equation (11).

$$H_i = Av_iT_i \tag{11}$$

Consequently, the yearlong electricity derived from crop type *i* (E_i) is computed as follows:

$$E_i(\text{MWh}) = \frac{H_i(\text{MJ})}{3600} \tag{12}$$

In (12), since 1W=1 J/s, H_i has been divided by 3600 s for converting energy in J to electric power in W.

III. Discussion on Results

Morocco's and Brazil's agricultural sectors can yield approximately 22 and 291 billion kilograms of agricultural waste, respectively, signifying a substantial and promising resource for generating power. In villages, common biomass sources like charcoal and firewood continue to play a pivotal role as essential materials for everyday residential cooking. However, this practice is not deemed sustainable and presents a host of challenges, particularly in the face of diminishing global forest reserves. These forests play a critical role in the carbon cycle, and their ongoing decline is exacerbated by reduced global rainfall and increasingly frequent natural wildfires [56], [57]. In the rural regions of Morocco, approximately 3 billion kilograms of farming leftovers are generated, making up approximately 95% of the nation's entire agri-biomass output. This waste is often situated at a considerable distance from energy generation hubs, which underscores the growing interest in decentralized electricity and heat production in the country. Figs 7 and 8 illustrate the proportion and distribution of cultivable districts across the nation.

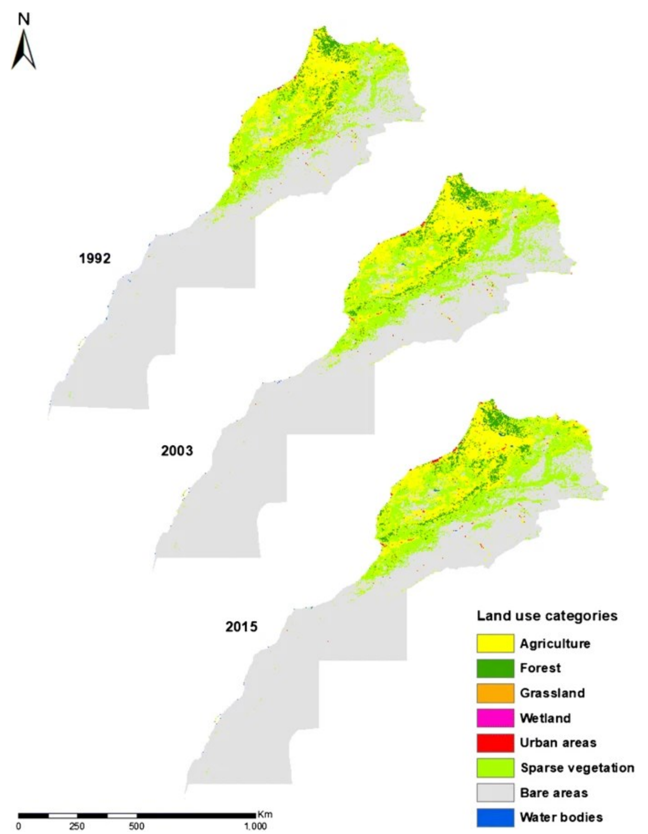

Fig. 7. Geographical dispersion of country's cultivable area [63].

Fig. 8 reveals that nearly 63% of Morocco holds the chance for distributed power generation from agricultural biomass. The availability of biomass is contingent on various elements, encompassing the yield of crops, the ratio of residues to the total crop output, and potential secondary utilization options for specific residues. However, Table A.I in Appendix provides an overview of the average residue yields per hectare across different regions [58]-[60].

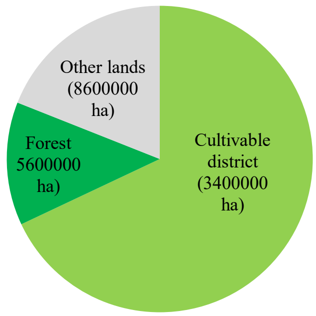

Fig. 8. The proportion of the nation's land utilization.

Considering the substantial influence of water content, as well as combustor heat loss and incomplete combustion on the output power potential of residue, Table A.II in the Appendix presents the mean water volume and usability amounts for a crop category. This information was compiled based on data sourced from [61] and [62]. According to equation (8), higher moisture content results in lower LHV, and therefore less energy generation based on equation (9). Furthermore, Table A. III (see Apendix) provides insights into the chemical compositions of various crop categories [63]. By drawing upon the data of Table A. III and the initial column of Table A. II, plus performing computations utilizing equations (8) and (7), Table I is compiled to depict the HHV and LHV of crop residues. It should be noted that the HHV values in Table I are close to the corresponding values calculated using experimental methods in [54].

TABLE I
RESIDUE'S VALUES OF HEAT FOR MOROCCO (GJ/T)

Residue	LHV	HHV
Peanut	9.0614	15.964
Sugarcane bagasse	10.2290	20.597
Sugar beet leaves	2.3617	16.776
Date palm	16.1654	18.233
Sunflower stems/leaves	13.4752	17.965
Market gardening pruning	0.4471	16.824
Citrus pruning	10.4764	18.228
Legume stems/straws	14.8496	16.771
Olive pruning	9.8702	18.079
Cereal straws	16.0470	19.310

Table II enables the determination of the upper and lower bounds for the country's theoretical energy potential harnessed through plant residues. This estimation is achieved through the application of relations (9) and (2), and the corresponding outcomes are showcased in Table I. The tangible range for real biomass energy production within Morocco can be ascertained using equation (11), taking into account the values from Table II and the final Table A.II column. Table III outlines the outcomes of this computation. Subsequently, Table IV elucidates the genuine capacity for generating electric power sourced from agricultural biomasses. This determination is founded on calculations performed using equation (12) and drawing upon the findings presented by Table III.

TABLE II
GROSS ENERGY PRODUCTION FROM VARIOUS RESIDUES IN MOROCCO (GJ)

Waste	Least	Peak
Peanut	114200	201100
Sugarcane bagasse	322200	648800
Sugar beet leaves	779400	5536100
Date palm	6705400	7563000
Sunflower stems/leaves	1754500	2339000
Market gardening pruning	478000	18003000
Citrus pruning	9190000	15990000
Legume stems/straws	2800000	3160000
Olive pruning	71070000	130170000
Cereal straws	213790000	257260000

TABLE III
REAL POWER PRODUCTION FROM RESIDUES IN MOROCCO (GJ)

Waste	Least	Peak
Peanut	91000	161000
Sugarcane bagasse	145000	292000
Sugar beet leaves	117000	830000
Date palm	4023000	4538000
Sunflower stems/leaves	1053000	1403000
Market gardening pruning	382000	14402000
Citrus pruning	7352000	12792000
Legume stems/straws	1050000	1185000
Olive pruning	35535000	65085000
Cereal straws	80171000	96472000

TABLE IV
ELECTRIC POWER GENERATED VIA RESIDUES IN MOROCCO (TWH)

Waste	Least	Peak
Peanut	0.0253	0.0447
Sugarcane bagasse	0.0403	0.0811
Sugar beet leaves	0.0325	0.2306
Date palm	1.1175	1.2606
Sunflower stems/leaves	0.2925	0.3897
Market gardening pruning	0.1061	4.0006
Citrus pruning	2.0422	3.5533
Legume stems/straws	0.2917	0.3292
Olive pruning	9.8708	18.0792
Cereal straws	22.2697	26.7978

The outcomes underscore the significance of cereals, olive biomass, citrus, and market gardening residues in the overall energy yield derived from agricultural residues in Morocco, largely due to the extensive cultivation of these crops. Despite legumes having a larger agricultural footprint compared to citrus arable lands, the energy potential derived from legume biomass is inferior to that of citrus residues. This discrepancy arises from the fact that legumes yield smaller quantities of biomass in comparison to citrus waste. According to the cultivation areas listed in Table V [64]-[71] and the data provided in Tables A.I and A.III, the total biomass and its heating values for Brazil can be presented in Table VI. According to equations (9) and (2), least and maximum gross energy obtained from biomass in Brazil is calculated as Table VII.

TABLE V
CULTIVATED AREA OF AGRICULTURAL PRODUCTS IN BRAZIL

Product		Mean cultivable lands (Thousand ha)
Peanut [71]		200
Sugar plants [70]	Sugarcane	8450
	Sugar beet	1050
Sunflower [69]		63
Market gardening [68]		701.2
Citrus [64]		930.6
Legumes [65]		2800
Olives [66]		20
Cereals [67]		27000

TABLE VI
BIOMASS AND ITS HEATING VALUES

Product	Biomass (t)	LHV(GJ/t)	HHV(GJ/t)
Peanut	120000	9.0614	15.964
Sugarcane	17745000	10.2290	20.597
Sugar beet	6300000	2.3617	16.776
Sunflower	132000	13.4752	17.965
Market gardening	1052000	0.4471	16.824
Citrus	10384000	10.4764	18.228
Legumes	1400000	14.8496	16.771
Olive	120000	9.8702	18.079
Cereal	67500000	16.0470	19.310

TABLE VII
GROSS ENERGY PRODUCTION FROM VARIOUS RESIDUES IN BRAZIL (GJ)

Waste	Least	Peak
Peanut	1100000	1900000
Sugarcane bagasse	181500000	365500000
Sugar beet leaves	14900000	105700000
Sunflower stems/leaves	1800000	2400000
Market gardening pruning	500000	17700000
Citrus pruning	108800000	189300000
Legume stems/straws	20800000	23500000
Olive pruning	1200000	2200000
Cereal straws	1083200000	1303400000

Finally, Tables VIII and IX show the actual potential of agricultural residues for bioenergy and bioelectricity generation in Brazil, which has been calculated using equations (11) and (12) and information from Tables VII and A.II.

TABLE VIII
REAL POWER PRODUCTION FROM RESIDUES IN BRAZIL (GJ)

Waste	Least	Peak
Peanut	880000	1520000
Sugarcane bagasse	81675000	164475000
Sugar beet leaves	2235000	15855000
Sunflower stems/leaves	1080000	1440000
Market gardening pruning	400000	14160000
Citrus pruning	87040000	151440000
Legume stems/straws	7800000	8812500
Olive pruning	600000	1100000
Cereal straws	406200000	488775000

TABLE IX
ELECTRIC POWER GENERATED VIA RESIDUES IN BRAZIL (TWH)

Waste	Least	Peak
Peanut	0.24	0.42
Sugarcane bagasse	22.69	45.69
Sugar beet leaves	0.62	4.4
Sunflower stems/leaves	0.3	0.4
Market gardening pruning	0.11	3.93
Citrus pruning	24.18	42.07
Legume stems/straws	2.17	2.45
Olive pruning	0.17	0.31
Cereal straws	112.83	135.77

Tables VI and VII show that Brazil has a higher potential for biomass production and energy generation from most agricultural products, except for olive and date palm residues, compared to Morocco. This is despite the fact that Brazil's sunflower cultivation is almost the same as Morocco's. It should be noted that Brazil does not produce date palms and relies entirely on imports for its supply. However, there is potential for date palm cultivation in eastern Brazil. In addition, Morocco's olive production surpasses Brazil's due to the more suitable Mediterranean climate for olive cultivation compared to Brazil's subtropical climate. In addition, Tables VIII and IX indicate that the greatest potential for energy and electricity generation in Brazil comes from cereal, citrus, and sugarcane biomass, respectively. Our findings indicate that mechanized agriculture and harvesting reduce residue waste, enhancing biomass energy generation. Cereal straw and date palm biomass have higher LHV and HHV than other residues due to lower moisture content and better chemical properties. Thus, Morocco and Brazil should invest in facilities to encourage farmers to cultivate these crops for more sustainable energy generation.

IV. RESULTS COMPARISON

Morocco, with 1.2 million hectares of land under olive cultivation, has almost twice the bioenergy potential of Jordan, which has 570000 hectares of olive cultivation [37]. Additionally, Morocco and Brazil, with 5.329 and 27 million hectares under cereal cultivation, respectively, have a cereal biomass yield of 2.5 t/ha. In contrast, Iraq has 2.12 million hectares with a residue yield of 2.6 t/ha for cereal, giving Morocco and Brazil 2.5 and 13 times Iraq's potential for energy generation from cereal waste [38]. The LHV of 15.5 MJ/kg calculated for cereal residues in [38] supports the accuracy of our LHV calculations for cereal biomass in Tables I and VI. Furthermore, the HHV of 18.4 MJ/kg estimated for olive residues in Turkey [39] verifies our HHV calculations for olive biomass in these tables. Moreover, the annual energy generation of 2605 TJ obtained from 204536 tons of agricultural biomass in Argentina [41] indicates the accuracy of the maximum real total energy generation estimates of 197160 TJ and 847577.5 TJ for 23.792 and 107.218 million tons of agricultural residues in Morocco and Brazil, respectively, given the proximity of the index of 0.01 TJ/t in [41] to the index of 0.008 TJ/t in our current research. Furthermore, the estimation of 63.93 TWh of electric power from a similar dry biomass weight in India [43] supports the correctness of the 54.77 TWh calculated in Table IV for total electric power generation. The generation of 96.36 TWh of electricity from 40 million tons of agricultural biomass in Pakistan (2.4 MWh/t) [45] justifies our estimates of 24 and 107 million tons of agricultural residues for generating 54.77 and 235.440 TWh (see Table IX) of electricity in Morocco (2.3 MWh/t) and Brazil (2.2 MWh/t), respectively. Finally, it should be said that the potential of 2.8 MWh/t for electric energy generation from citrus residues in Colombia [48] is close to the 3 MWh/t average electric energy obtained from citrus wastes in Morocco (Table IV).

V. CONCLUSION

The industry of electricity in Morocco and Brazil should prioritize the adoption of sustainable power such as biomass, hydro, solar, and wind, over natural fuel-based energy production. This shift is imperative to mitigate the substantial costs linked to fossil fuel imports and LNG production, and to reduce the associated CO_2 emission. However, hydroelectric power generation in Morocco and Brazil is on the decline, primarily attributed to diminishing rainfall and persistent natural drought conditions. Furthermore, wind and solar power generation in these countries are characterized by uncertainty and necessitate the implementation of costly storage systems to ensure a secure and reliable energy supply. As a result, biomass power generation stands out as a practical and sustainable option for renewable energy generation within the Moroccan and Brazilian power sectors. The focus of this study was to evaluate the capacity for generating energy from agricultural residues in Morocco with useful lessons for Brazil. To achieve this objective, we conducted assessments to estimate both the gross and practical capability of power production from biomass derived from key Moroccan agricultural commodities. These commodities include cereals, olives, legumes, citrus fruits, market garden crops, sunflowers, sugarcane, sugar beets, date palms, and peanuts. The findings of this study highlight the substantial potential that Morocco possesses for generating biomass power through the utilization of agricultural residues. Such an approach has the potential to address the economic and environmental challenges associated with fossil fuel consumption in Morocco, including mitigating import expenditures and reducing greenhouse gas emissions. The same mathematical methods and strategies used in the current research were applied to the equal agricultural residues in Brazil, with the exception of date palm. The findings of this paper can assist researchers in calculating the bioenergy and electricity generation potential of all other crops in Morocco and Brazil. The cost of developing new biomass power plants is not discussed in this paper. Researchers may consider addressing this issue in future studies. Also, due to a lack of access to precise information about biomass yields in each region, average values for each residue yield have been presented in this paper. However, considering the variation in residue yields across different regions can be a future research direction.

Appendix: Data

TABLE A.I
CULTIVATED AREA AND YIELD OF CROP RESIDUES

Product		Mean cultivable lands (Thousand ha)	Biowaste (kg/ha)
Peanut		21	600
Sugar plants	Sugarcane	15	2100
	Sugar beet	55	6000
Date palm		61	6800
Sunflower		62	2100
Market gardening	Others	10	1500
	Tomato	18	20200
	Banana	30	20000
	Potato	61	1500
Citrus		129	6800
Legumes		377	500
Olives		1200	6000
Cereals		5329	2500

TABLE A.II
WATER VOLUME AND RESIDUE'S USABILITY

Residue	Water	Usability
Peanut pruning	0.375	0.8
Sugarcane bagasse	0.45	0.45
Sugar beet leaves	0.75	0.15
Date palm	0.1	0.6
Sunflower stems/leaves	0.22	0.6
Market gardening pruning	0.85	0.8
Citrus pruning	0.375	0.8
Legume stems/straws	0.1	0.375
Olive pruning	0.4	0.5
Cereal straws	0.15	0.375

TABLE A. III
RESIDUE'S NITROGEN, CARBON, AND HYDROGEN VOLUME

Crop Residue	N	C	H
Peanut	0.0127	0.3938	0.0548
Sugarcane bagasse	0.0118	0.5146	0.0588
Sugar beet leaves	0.0099	0.4208	0.0632
Date palm	0.0082	0.459	0.0579
Sunflower stems/leaves	0.0038	0.4533	0.0591
Market gardening pruning	0.0164	0.4201	0.0645
Citrus pruning	0.0031	0.4534	0.0885
Legume stems/straws	0.012	0.4202	0.0643
Olive pruning	0.0147	0.4536	0.0547
Cereal straws	0.0143	0.4811	0.0629

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