THE IMPORTANCE OF SELF-GENERATION OF ELECTRICITY THROUGH CONTROLLED RECYCLING: A CASE STUDY IN WEST SUB-SAHARAN AFRICAN REGIONS

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ABSTRACT

Controlled recycling of different materials, typical to household appliances, from the landfills located in developing countries in West Sub-Saharan Africa and their subsequent reuse can favour the social, economic and environmental sustainability of the involved regions. This process reduces the unhealthy conditions associated with landfills and the inadequate use of fuels, and it also solves certain deficits in the population. As a continuation of previous studies, this article proposes a practical example of manufacture through the controlled reuse of an asynchronous wind-powered electricity generation system, analysing the benefits and possibilities detected, especially in domestic self-generation and in the reduction of CO_2 emissions into the atmosphere. In summary, the topic is the manufacture of an energy generating system using recycled material for domestic use. In this way, the associated self-generation of electricity can supply or reduce the energy demand of a large part of the population in these regions that do not have electricity supply; for example, for a household in Nigeria, it would save between 15% and 75% of the electricity supply. Providing electricity supply also prevents deforestation in regions that use natural biomass as an alternative energy source, an issue that has a global impact on CO_2 emissions into the atmosphere.

Keywords: controlled recycling, deforestation, emissions, landfills, wind power.

1 INTRODUCTION

The health of the population of certain regions is in difficult situations, due, among other factors, to inadequate work and power supply methods, which imply diverse synergies with great social, economic and environmental consequences.

The working methods used in international landfills in West Sub-Saharan Africa are the consequence of shortening of the life cycle of some technologies, which leads to the substitution of certain equipment that still has different benefits and possibilities, thus promoting a short life cycle and an early technological obsolescence of electrical and electronic equipment [1, 2]. All this implies a significant increase in electrical and electronic waste and the international use of certain regions as landfills [3, 4]. Areas such as West Sub-Saharan Africa [4, 7] and Agbogbloshie, in Accra, Ghana [8], are destinations of waste from all over the world. Moreover, certain regions, such as Nigeria and Ghana, do not have laws for the treatment of waste [9]. Given this situation, reuse in the very landfills has been proposed as a solution [1, 10] and this offers the most disadvantaged population an economic opportunity [7, 11, 12]; however, the typology of electric-electronic waste [9] and the lack of resources and training of the population [1] involve unsafe and unhealthy conditions [2, 5, 11], thus generating proven and quantified environmental impacts [1, 2, 4, 5, 11, 13]. In addition to this, the laws on child protection to prevent child labour (13–15 years of age) are not properly applied and controlled, which, along with the existing economic needs, allows minors to

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work in the landfills [14], leading to a large number of early deaths associated with the exposure to toxic emissions and substances from the landfills [12].

Furthermore, with regard to energy supply problems, most of the regions used as international dumping grounds are considered by the International Energy Agency to be in a situation of 'electricity poverty' [15], with great technical and economic difficulties in accessing electricity [16], with less than 50% of the population in countries such as Mauritania, Togo and Benin, and 23–25% in Burkina Faso and some regions of Nigeria [17]. As an example, in West Sub-Saharan Africa, 57% of schools do not have electricity and 60% of health centres do not have a reliable supply [18]. The lack of power supply forces the population to resort to forest biomass to cover their priority energy needs, being almost 90% of the total energy used [17, 19]. At the home level, the use of mainly wood and charcoal (coal produced from the combustion of wood, obtaining greater calorific value), through traditional methods of poor quality and yield, is associated with a large variety of risks to the health and well-being of women and children [20]. Moreover, the use of the forest area as priority fuel, along with a significant growth of the population [6, 21, 24] are causing an unsustainable deforestation of the regions, with the subsequent emission of large amounts of CO_2 to the atmosphere, which indirectly contaminates the water of rivers [21, 23, 25], thus hindering the progress of other activities, such as the fishing industry.

To sum up, both uncontrolled recycling and the use of forest biomass as energy fuel involve health problems and early death in the population, as well as negative impacts on the environment.

This article continues with the process of recycling the wind turbine, specifically the rectifier, in the workshops and school workshops located in the education centres including laboratory tests.

Subsequently, the advantages of a wind turbine made from recycled material in a typical house in Nigeria are presented.

2 PROBLEM IDENTIFICATION AND PROPOSITION

A practice is here proposed, similar to one developed in the University of Cantabria with learners from the West African country of Benin, that reduces the negative impacts commented in the Introduction. In the Spanish region of Cantabria, a training course was taught to adolescents about the reuse of computers, especially CPUs, that were obsolete, in developed countries and which could be found in landfills at zero cost. Very positive results were obtained both in the practical training of the youths and in the recovery of equipment for later use as personal computers at home or in education centres, enabling the participants to do the maintenance and technical repairs themselves in the future. Later, during a stay in the University of Kara, in Togo, and observing the habitability conditions, it was proposed to carry out the experience in this region in situ.

Therefore, in agreement with previous studies [21, 23], the present article proposes the realisation of an adequate process of controlled reuse (Fig. 1) of electric and electronic products that exist mainly in landfills [1, 9] for the manufacture of a small wind-powered electricity generation system. This will be carried out in the workshops and school workshops located in the education centres where the learners undertake their practical training, which, in some cases, are also linked to the subsequent commercialisation of the manufactured products, whose manufacturing cost is quite low, since the working hours of the students and a considerable part of the material are free [9].

Thus, this proposition provides professional training and opportunities for autochthonous adolescents, preventing unhealthy activities in the landfills. At the same time, this project

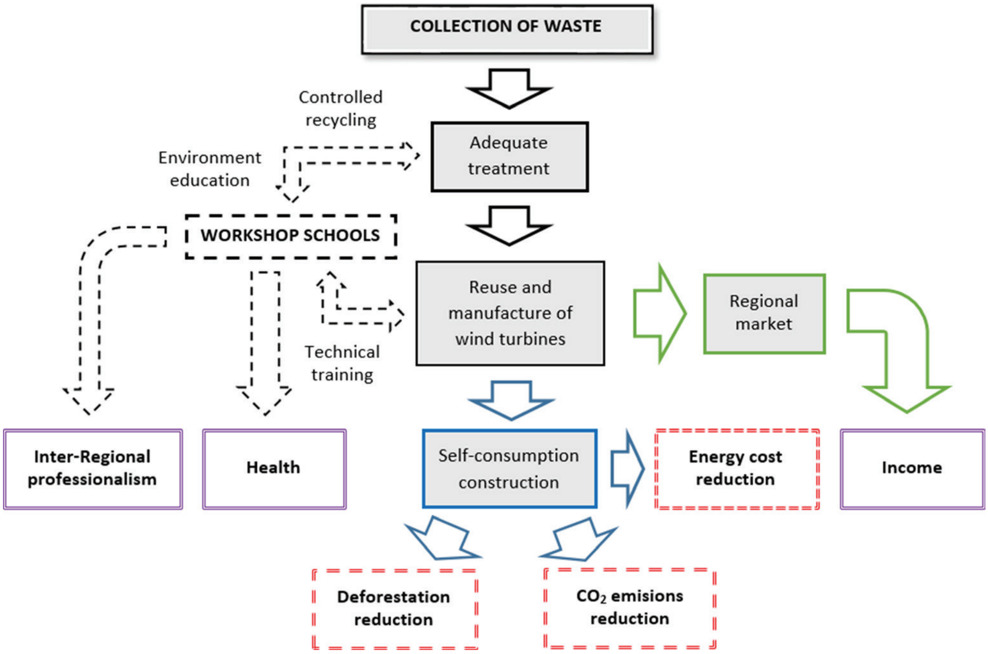


Figure 1: Diagram of the process and possibilities offered.

allows covering energy needs in the surrounding regions, which implies a cost reduction in the electricity bill, and it offers the possibility of commercialising the manufactured equipment and a decrease of the environmental impacts associated with the use of other energy resources, such as forest biomass.

The present article specifies and expands previous studies [21, 23] about controlled reuse for the manufacture of a wind-powered electricity generation system, describing new stages of the process and presenting the experimental results obtained through laboratory trials. Then, from the estimations obtained from the experimental trials, the energy benefits found are described and some of their corresponding contributions, highlighted in red in Fig. 1 are evaluated: economic due to reduction of electricity consumption and environmental due to decrease of deforestation and CO_2 emissions.

3 PRACTICAL METHODOLOGY FOR THE MANUFACTURE OF A WIND-POWERED ELECTRICITY GENERATION SYSTEM

The experimental practice proposes the manufacture of an electricity generation system composed of a small-power wind turbine and a converter for signal processing. A signal output in direct voltage was selected, in order to enable the storage of energy in batteries, although it could also be used as an autonomous electricity system of the direct voltage network and thus reduce the loss in the processing [25].

For the adequate controlled reuse of landfill waste, a series of specific tasks were considered: selection and location of materials, and their subsequent treatment and assembly [21, 22]. Next, an estimation of the benefits of the electricity generation system is provided, through the corresponding laboratory trials conducted.

The treatment, assembly and trials were carried out in the mentioned school workshops [21].

3.1 Wind-powered electricity generation system

3.1.1 Preparation of materials and assembly of the electricity generation machine

Initially, the aim was to build a synchronous generator with a permanent magnet rotor; in this case, the stator and the rotor of the electric machine can be obtained through different means, developing a recycling and preparation process, all that conducted in a controlled manner and requiring small mechanical adjustments in the worst case.

In landfills, it is possible to find mainly permanent magnet motors and squirrel-cage motors with capacitor and universal start. Although the former can work as generators without modifications, the latter can work with elevated pairs for functioning (washing machines, driers, centrifuges, etc.), which is interesting, considering that the machine, as a generator, will reduce the value of its nominal power. Moreover, the stator of the squirrel-cage motor (Fig. 2a), since it is designed with stacked veneers in a symmetric set of salient poles (easy to identify), with the corresponding coils that generate the induction on the rotor, enables its preparation for use as a generator without the need of complicated adaptations, and it also allows for an adequate subsequent adaptation of the rotor.

Based on previous studies [21, 22], the rotor was obtained through the adequate disposition of the corresponding number of permanent magnets to generate the proper constant magnetic field. The magnets of computer hard drives, which are made from an alloy of iron, boron and neodymium, have great field intensity and are obtained from 3.5″ HDD hard drives, which are abundant in landfills and suitable for cutting and carving, with the possibility of producing magnets of 20 × 10 × 5 mm. Microwaves also contain two magnets, in this case made of ferrite, usually in cylindrical rings of approximately 58 mm in outer diameter and 13 mm in depth.

To design the rotor, the axial and radial dispositions were used. In the axial disposition, the axis of rotation is parallel to the magnetic field of the magnets and the stator slots radially. In the radial disposition, the axis of rotation is perpendicular to the magnetic field of the magnets and the stator slots axially (Fig. 2b). In the case of the neodymium magnets, depending on the typology of the generator, both dispositions can be admitted for the magnets. In the specific case and as an advantage of the radial disposition of the magnets, the field value required can be established through the simple symmetric stacking of magnets,

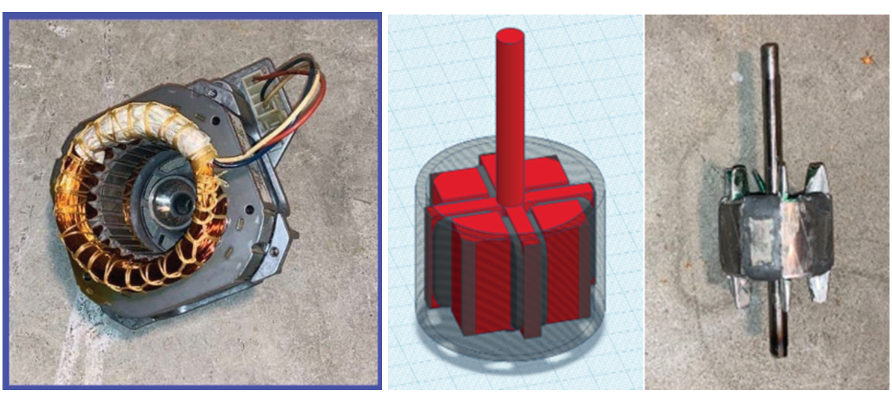


Figure 2: (a) Stator for the trial from reused material, (b) disposition of the rotor and structure used experimentally from reused material.

based on the requirement. Then, depending on the stator prepared and its data (dimensional, structural and electrical), the corresponding dimension and disposition of the magnets of the rotor are designed, in order to obtain the required magnetic flux for the dimensional limitation found.

3.1.2 Signal processing

There are different possibilities to obtain a direct output voltage of a certain value. Among these possibilities, the regulator-rectifier system shown in Fig. 3 is an economic and feasible solution to reuse the control cards of equipment found in electric-electronic landfills.

The obtained output of the electric machine is a signal with significant distortion, which is inversely proportional to the lack of homogeneity in the magnetic flux of the air gap. In the laboratory trials, the output signal of the electric machine was analysed by making the rotor of the motor rotate directly at a constant regime of 2100 rpm, which, through a full diode bridge, obtained from an electronic power card from the landfill, was converted to the rectified signal of Fig. 4a.

It is worth highlighting the importance of selecting, in the landfill, a diode bridge for voltages close to the working voltages, since, if others are selected, e.g. for voltages of 500 V, in addition to the deterioration of the functioning, losses of up to 26.25% can be reached in the rectification process. This can be avoided almost completely with the adequate diodes. Then, to obtain an almost perfect DC signal, an electrolytic capacitor of 47 µF was added, which was also obtained from a recycled plaque, parallel to the output of the rectifier bridge, thus obtaining a signal with negligible ripple. For the recycling of the electrolytic capacitor, it presents an admissible tolerance of 20%, which is an interesting aspect for its reuse, although electrolytic capacitors deteriorate with time, which must be avoided in order to maintain the benefits.

Lastly, a voltage regulator LM78XX (Fig. 3) was incorporated, designed for obtaining an adequate linear voltage to feed the set of batteries, whose value will depend on the charge value. Figure 4b shows the characteristics of the obtained response and the recommended working values. In this way, a simple stage was incorporated, through recycled components of great availability, which supplies a constant charge voltage with electronic regulation and interrupting the current when it reaches a minimum value.

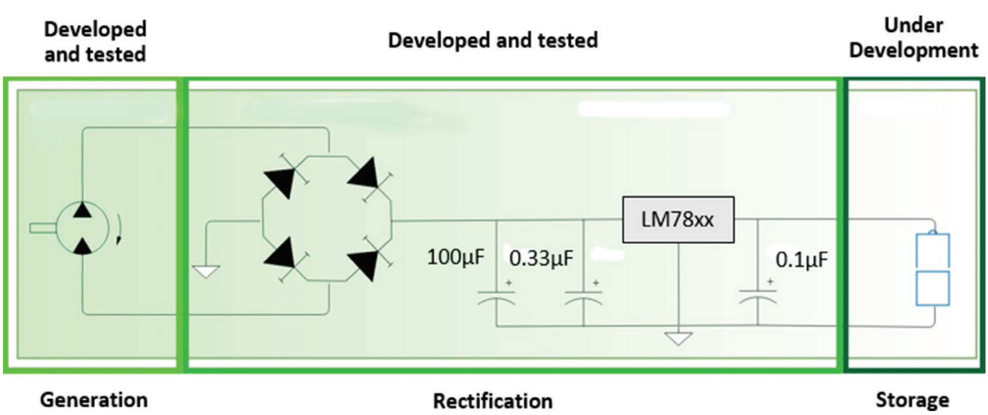
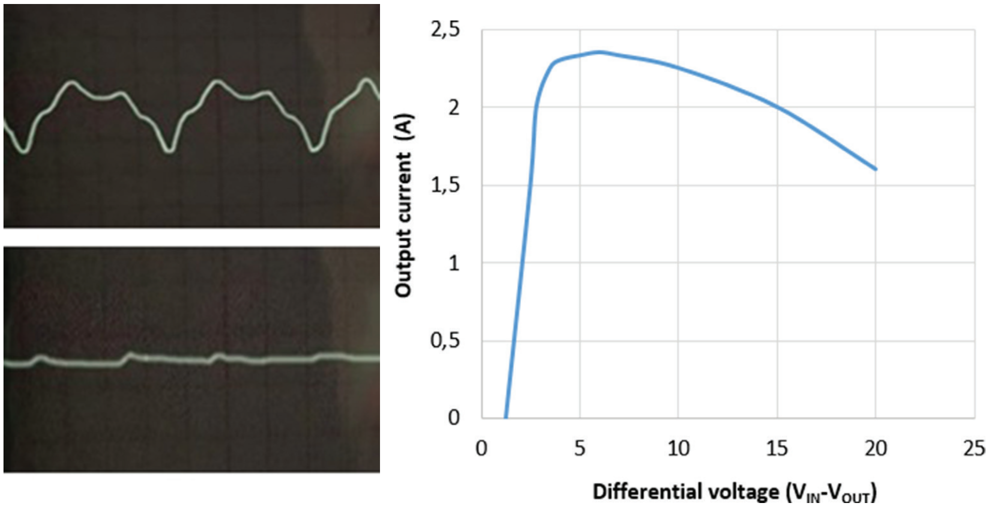


Figure 3: Electrical energy generation, conversion and storage system.



(a) (b)

Figure 4: (a) Output signal of the electric machine rectified with and without electrolytic capacitor, (b) voltage regulator output.

3.2 Experimental tests and trials

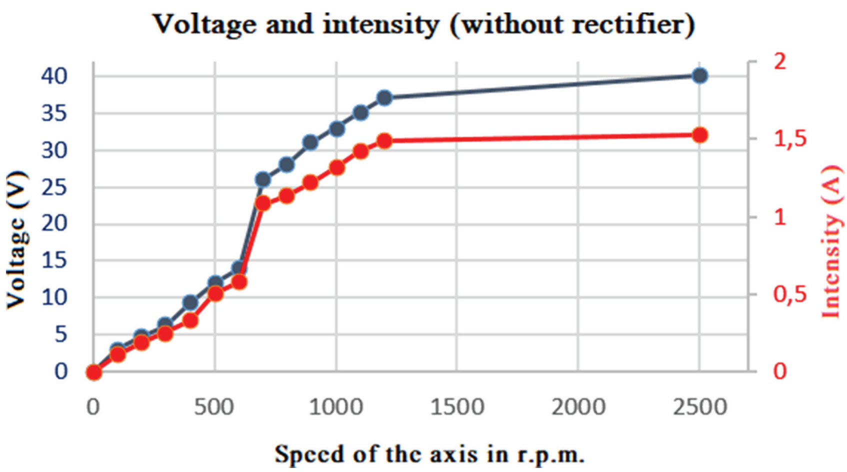
In the laboratory, with the electricity generator machine ready, a compound motor was used to make the generator and the corresponding measurement instruments rotate (Fig. 5a). The first experimental trials showed a linear character with the generator empty and charged, given the proportionality of the flux with intensity, and acceptable output characteristics for different charge values, despite the amorphous design of the rotor, with a heterogeneous air gap [21, 23]. To observe its behaviour with the rectifier circuit connected to the output of the wind turbine, a rectifier input impedance close to 6 ohms was calculated, by serial connection of the inner coil of the stator, in a way that, with the progressive increase of the velocity imposed by the compound motor, the voltage and intensity curves of Fig. 5b were obtained.

To compare the results between the different behaviours of the machine according to the possible connections of the inner coil of the stator (individual, serial and parallel), the curves that relate the active output power to the revolutions provided by the compound motor were obtained for various types of connection of the stator coil (Fig. 6).

To extrapolate the obtained results to curves that relate the power to the wind speed, it was assumed that a multiplier mechanic system of gears exists depending on the configuration (5/1 ratio in individual configuration, 8/1 in serial configuration and 6/1 parallel configuration).

The obtained experimental curves show that the serial configuration of the coil provides more power and a better response for slow winds, contributing a greater factor of hours of use in the power generation of the electric machine. With a minimum production close to 3 m/s and reaching the nominal power elbow at around 7 m/s, an adequate electric machine was obtained for very slow winds and low-resource areas. Adjusting the ratio of gears, the machine can be adapted, to a greater or lesser extent, for the type of resource available.

(a)



(b)

Figure 5: (a) Laboratory test bench, (b) voltage and intensity as a function of the velocity of the electric machine tested.

4 BENEFITS AND ANALYSIS OF THE RESULTS

From the trials conducted and valuing a better technique of the benefits of the wind turbine with the improvement of the process, a starting electrical power of 30 W was estimated; the machine could be applied in the construction sector in different regions of Africa, where varying wind values have been obtained in a period of 30 years, using squares of 75 km^2 with stations located 100 m, above the sea level, in the air. For example, in Northern Ghana and Togo, an average wind speed of 4–5 m/s has been recorded, whereas in part of Nigeria and Burkina Faso the wind speed recorded was 5–6 m/s, reaching 7–10 m/s in Mauritania and in Western Sahara [15].

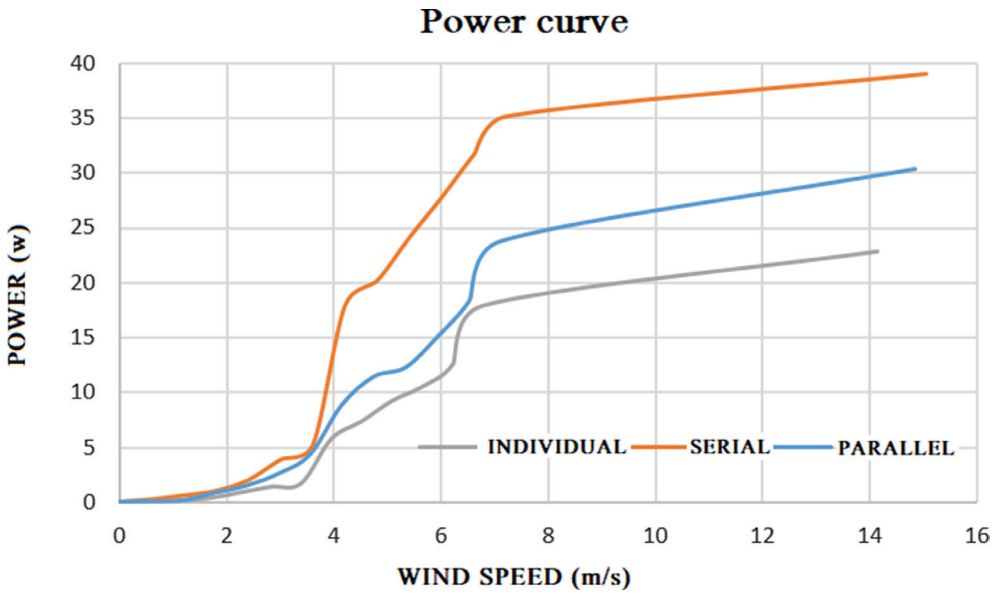


Figure 6: Power curves as a function of the connection of the stator coil.

Table1: Possible power demand of a home.

Receptors	Typology	Power	Room-Hour	Energy/Day
Luminaire	Incandescent or similar	40 W	2 × 3 h	240 Wh
Mobile charger	5–6 V–0.5 A	2.5–3 W	1.5 h	3.75–4.5 Wh
Heating plaque	Electric resistance	500–600 W	1.5 h	750–900 Wh

Therefore, some of the tangible benefits of manufacturing wind turbines through controlled reuse can be valued, such as the self-generation of electricity and the reduction of CO_2 emissions to the atmosphere from deforestation.

4.1 Electricity self-generation

An estimation of 2,500 hours of use based on the wind speeds mentioned above [15] would yield an approximate production of 75 kWh per year.

Table 1 shows the power demand of a house of 2–3 people connected to the power grid, taking into account: the existence of incandescent luminaire or similar, which is the predominant use of the region [26], the use of basic appliances for heat generation in the kitchen and the use of mobile devices. It is worth highlighting the importance of the kitchen in the power consumption and that around 50% of the population use mobile phones, which, in Nigeria, involves around 90 million active lines. This estimation yields an annual consumption between 363 and 417.7 kWh/year per home.

This power demand is in 40% of homes of West Sub-Saharan Africa, where the average annual consumption is between 100 and 500 kWh per year, depending on the type and performance of the receptors used [17]. For a house in Nigeria, where this type of user does not pay fixed tolls in the electricity bill, this would pose an economic saving of 15–75% of the total amount paid for power supply. This would be a highly relevant reduction, considering that, in Nigeria, over 50% of the population live with less than 2 dollars per day [16]. Moreover, if part of the activities were conducted by other means and if it were possible to reach full electricity self-consumption, without the need to connect to the power grid, the economic saving would be even greater in those regions where there are fixed connection tolls in the electricity bill.

By participating in the electricity self-generation system developed experimentally through wind power, with a direct voltage output signal, adapting the grid of the building, it is possible to avoid the cost of signal inversion and the losses associated with all the necessary energy conversions, allowing the direct charging of batteries and storage of electricity [25].

In this way, both partial and total self-consumption of the building would greatly favour the population and the power system. This is due to the fact that the proposed self-generation system would facilitate the supply of the most disadvantaged areas, which, for the particular case of Togo and Nigeria, are those less populated and further away from the coast to the north, where, incidentally, the wind is stronger [15]. Moreover, self-consumption would prevent the losses generated by the transport of electricity and the faulty connections, since a large number of electricity generation plants are located near the coast for reasons related to the import of primary resources [26], and the reach and quality of the power system in the northern regions is deficient [25].

4.2 Reductions of emissions to the atmosphere and deforestation

Apart from the use of a renewable resource such as wind power, with the consequent reduction of emissions, the only alternative available to the population is the use of fossil fuels or forest biomass.

4.2.1 Reduction of emissions observed with the decrease of power demand in homes with power supply

Considering that the replaced electricity is from the electrical supply, then, for example, in Nigeria, where every kWh of the power grid is generated by energy from 75.6% gas, 18.6% hydroelectric and 5.8% coal, and the electricity transport has mean losses of almost 9% (reaching 19% in exceptional moments) [27], emissions of 203.66 g of CO_2 eq/kWh are generated, taking into account the emission factors of fuels according to the experimented generation methodologies [28]. Therefore, a wind turbine like the one presented in this study would prevent 229.11 kg of CO_2 eq throughout a life cycle of 15 years. These emissions would be higher in other electricity generation systems such as those that exist in other regions.

However, if the electricity generated by gasoil generators were replaced, considering a factor of 80% of the generator machine, 61.1% of emissions would be prevented with respect to the previous case, without considering other factors related to the typology of generation that would further increase the emission.

4.2.2 Reduction of emissions and deforested area when reducing the consumption of forest biomass as an energy resource

When valuing the emissions according to the decrease of forest biomass used to generate energy, it is fundamental to take into account that, in addition to reducing the emissions, the deforestation of the forest area is also being prevented. As is already known, the emission of CO_2 emitted in the combustion of forest biomass is regarded as null [29], although this is considered when the amount of biomass combusted is equal to the reforested biomass. Therefore, the present analysis considered the deforested area per inhabitant that was not reforested naturally or by means implemented by the corresponding administration.

To quantify the reduction of emissions of non-reforested area, through the proposed self-generation system, the following aspects were considered: 1) only the deforested area that was not reforested in the region was taken into account; 2) the proportion of 89% of the forest biomass having power purposes was applied; and 3) the population that uses mainly forest biomass for cooking and similar purposes was only considered.

Mains electricity and development are linked to the typology of energy supply, with the population with higher income being the ones with exclusive access to gas and electricity to cover 100% of their power needs. In Nigeria, 73% of the population use forest biomass to cook [17], regardless of whether they have connection to electricity, since the homes of peri-urban and rural regions, with possible availability to forest biomass free of charge, use electricity only for lighting or similar purposes [20]. With these considerations, for Nigeria, where the deforested area in 2015 was 409,600 ha, it is estimated that each inhabitant involved, despite the natural and organised deforestation, removes 27.93 m^2 of forest surface annually to cover their energy needs.

In the region of Nigeria, the consumption of wood per capita in the rural area is 393.43 kg/year, whereas urban homes, where other alternative fuels are much more available, consume 255.75 kg/year [17, 24]. In this way, it can be considered that the power demand of wood is exclusively dedicated to the generation of thermal energy; in fact, the estimation of the electricity demand presented in Table 1 shows that, even with a reduced estimation in the use of appliances for the generation of heat, there is a supply for the generation of heat close to 80% and close to 90 kWh/year for lighting. These data confirm the consideration of electricity consumption between 100 and 500 kWh/year, since the first 100 kWh seem to be used for lighting and similar purposes, and the remaining 80% would be used for heating.

To determine the avoidable emissions and deforestation, it is considered that the basic consumption of electricity of a home is 500 kWh/year, with standard appliances [17], and estimating two people per home. Thus, assuming that the self-generation equipment covers part of the power demand used for heating, replacing wood as a resource, a reduction of 18.75% of the energy required is obtained.

Furthermore, it is also considered that 40,000 tons of wood from mixed species in uniform density require 3,600 ha of forest surface for annual generation [24], which implies a density of 11.1 t/ha per year, a value close to the forestation rate with mangroves, with a production of 12–20 t/ha per year of wood characteristic of Western Africa. Therefore, the surface removed, irreversibly, by the need for energy resources (mainly cooking) poses 31 kg/year per capita, which results in 9.55% of the forest biomass being consumed by people annually for an intermediate consumption between inhabitants of rural and urban areas.

Thus, the use of the electricity self-generation system would prevent almost double the gap that currently exists in the consumption of forest wood and the deforestation of the region. Through a minimum estimation of the emission prevented in the region of Nigeria with the previous considerations, valuing only the non-recovered biomass, the reductions per home/year were obtained (Table 2).

Considering the total forest biomass used for the energy needs, it could be established that, if 0.1% of the population of Nigeria had a wind turbine of 30 W, the emission of almost 40 t/year of CO_2 to the atmosphere would be prevented. Therefore, the obtained data high-

Table 2: Estimation of the reductions per home/year in Nigeria with wind energy in housing.

Reduction of the consumption of wood per home/year	62 kg/year
Reduction of emissions per home/year	113.67 kg CO_2/year
Reduction of the deforested area (two people)	Over 55.86 m^2/year

light the relevance of energy self-generation, especially in regions whose alternative fuel is forest biomass and the significant growth of the population hinders the regeneration of the natural forest surface, requiring extraordinary measures to maintain the biological cycle of the environment.

5 CONCLUSIONS AND FUTURE RESEARCH LINES

This case study presents a controlled recycling process for the possible utilisation of discarded materials for energy production, demonstrating the opportunities through pilot testing. In this way, several problems encountered in disadvantaged regions are solved, highlighting the possibility of obtaining the necessary materials and demonstrating the opportunities offered through pilot testing, showing that proper management opens up a wide range of benefits for the population involved. In the present study, the following aspects were incorporated and described:

- The conversion stage was incorporated in the electricity generation system for a correct processing of the output signal and to allow a supply of direct voltage or the charging of a set of batteries.
- A new experimental trial provided greater fidelity to the functioning and benefits of the electricity generating machine and its possible adaptation to the needs with an approximate power of 30 W.
- More thorough evaluation of the tangible benefits of energy self-consumption has been conducted. It has been shown that economic savings in the electricity bill (by reducing 15–75% the power consumption in 40% of homes of West Sub-Saharan Africa) and a significant mitigation of the environmental impact quantified in Table 2, lessening the emissions to the atmosphere and the deforestation of the regions, highlighting the relevance of self-generation of heat in regions whose alternative fuel is forest biomass.

In addition, this proposition provides professional training and opportunities for autochthonous adolescents, preventing unhealthy activities in the landfills.

Regarding future research lines that complement the results of this study, it is proposed to complete and improve the power generation system and incorporate it to the power grid, to improve the manufacture and benefits of the wind turbine and adapt it to the possibilities of wind power in the different regions; in addition, to carry out a more exhaustive economic evaluation of the tangible data proposed and assess the intangible data, such as the training of adolescents, health and working hygiene and economic cooperation among the neighbour regions, as well as the global benefits in terms of sustainability and conservation of the environment. Finally, to extrapolate the controlled recycling process to other generation means (solar, hydroelectric, etc.) applicable to similar regions, in order to establish alternatives that better suit their location and geographic characteristics.

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