Design and Implementation of an Experimental Thermoelectric System From Wood Waste

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Abstract

This study was carried out at Dino & Fils SA, a wood processing unit in Soa-Cameroon. The aim was to recover energy from wood waste in order to contribute to greater energy flexibility in wood processing units. Specifically, the aim was to assess the quantity of wood waste available on the site and estimate its energy potential, to design and test a system for producing electrical energy from these waste and to estimate the contribution of this thermoelectric system to meeting the company's energy needs and the associated costs. Wood waste were characterized by taking measurements at each station on the production line, supplemented by monthly production reports and scientific data. For the month of March 2024, the plant produced 3 284 m³ of wood waste, or 64% of the gross wood volume. This is equivalent to 2 766 tons for an electrical energy potential of 571 MWh; the company's monthly electricity consumption is estimated at 121 MWh. The experimental thermoelectric system set up, using the TEC1-12715 Peltier module, produced electricity with a total power of 841 W and a Seebeck coefficient of 0.04 $V°C^{-1}$ by burning 5 kg of sawdust for 85 minutes. On a real scale and under optimum conditions, this system would be an effective and viable solution for covering not only all the energy needs of Dino & Fils SA but also those of surrounding households and offices at a competitive cost of 48 FCFA/kWh.

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Keywords: Wood waste; recovery; electricity; Seebeck effect

Introduction

Cameroon's forests, with a total area of around 22.5 million hectares or 42% of the national area, form the second largest forest complex in Central Africa (Tchinda, 2015; MINFOF, 2019). Those that can be exploited for timber cover an area of 18 million hectares (GICAM, 2020). Between 2012 and 2017, average annual timber production was around 2.8 million m^3, with a processing rate of 75.35% (MINFOF, 2019). However, timber industries in Cameroon have a low yield of processed products, generating large quantities of waste in the form of sawdust, shavings, bark, etc. (FAO, 2015). Although often regarded as waste, these wood waste may have significant energy potential. Converting wood waste into electricity via thermoelectric modules offers an opportunity to diversify energy production and promote more sustainable resource management (ATIBT, 2011; Donizeau, 2001; Gerard, 2004).

Dino & Fils SA sawmill is supplied with electricity by the Cameroon's national electricity utility called Energy of Cameroon (ENEO) and by an increasingly energy-hungry generator running on diesel, a fossil fuel. The high dependence on ENEO prevents this company from producing full time in the event of a power cut. Would on-site recovery of wood waste be a viable alternative for diversifying or even replacing current energy sources at Dino & Fils sawmill? It is to this research question that we will attempt to provide a convincing answer during the course of this work. The general objective is to contribute to energy flexibility in wood processing units through a better wood waste management. The specific objectives are as follows:

- To characterize the wood waste of Dino & Fils SA;
- To design and implement a thermoelectric recovery system for these wood waste;
- To estimate the contribution of this system to meeting the company's electricity needs and the associated costs.

Material and Methods

Presentation of Dino & Fils SA

Dino & Fils SA is located at Nkolfoulou, in the Soa district, Mefou and Afamba Department, Center Region of Cameroon (Fig. 1). It is classified in the first category, as its annual log consumption exceeds 5 000 m^3 (MINFOF, 2012), and is involved in primary, secondary and tertiary wood processing. The study was carried out from February 01 to May 31, 2024 and focused on their primary processing, whose products (green lumbers) supply the other wood processing stages.

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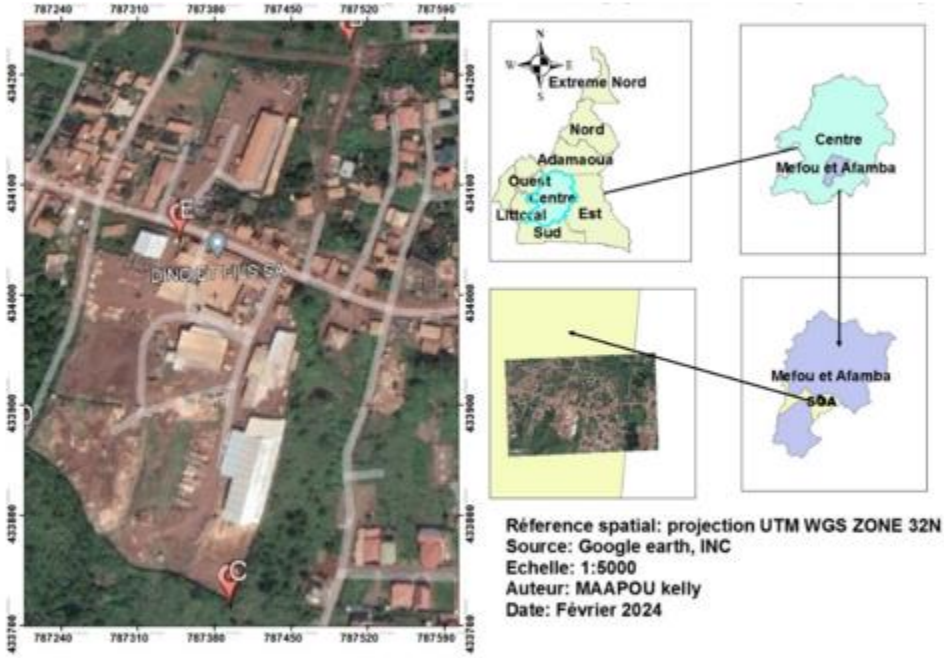

Figure 1. Localization of Dino & Fils SA

Characterisation of wood waste

Classification and quantification of wood waste

The wood waste were classified into different types based on their physical characteristics (size, shape, dimensions, colour, texture and possible presence of bark).

The length, width and thickness on all the pieces at the exit of the machine were measured with a tape measure, and the quantity of sawdust and offcuts produced daily were recorded. The data were then processed using an Excel spreadsheet and analysed in order to determine the volumes and proportions of each type of wood waste.

- Wood waste from the Lucas Mill

The quantity of wood waste was determined mainly by calculating the volume of slabs, edgings and sawdust using equations [1 – 5] using a sample of 16 logs sawn per day at the Lucas Mill.

- Calculation of the Volume of a log

$$V_{b1} = \frac{\Pi}{4} . D^2 L \quad (1)$$

V_{b1}: Volume of the log in m^3
D: average diameter of the log in m L: length of the log in m

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- Calculation of the volume of the cuts obtained (finished products)

$$v_p = L_P \cdot l_p \cdot e_p \cdot N_p \tag{2}$$

v_p: volume of finished products in m^3
L_P: length of the pieces in m
l_p: width of the pieces in m
e_p : thickness of cuts in m
N_p: number of pieces

- Calculation of the volume of sawdust

$$V_{S_1} = N_T \cdot \lambda \cdot L_T \tag{3}$$

V_{S1}: volume of sawdust in m^3
N_T: number of saw cuts
λ: saw kerf thickness in m
L_T: saw cut length in m

- Calculation of the volume of the edgings

$$v_{de_1} = N_P \cdot L_p \cdot l_p \cdot e_p \tag{4}$$

- Calculation of the volume of the slabs

$$v_{D_1} = V_{b1} - (v_P + V_{S_1} + v_{de_1}) \tag{5}$$

- Wood waste from the horizontal saw (CD10) and edger

The quantity of wood waste was determined mainly by calculating the volume of slabs, edgings and sawdust using equations [6 – 12] using a sample of 48 logs sawn per day at the CD10.

- Calculation of log volume

$$V_{b2} = \frac{\Pi}{4} . D^2 L \tag{6}$$

- Calculation of sawdust volume

$$V_{S_2} = \lambda \cdot L_T \cdot \sum_{c=1}^{n} c \tag{7}$$

$$c = \sqrt{4f(d - f)} \tag{8}$$

λ: saw kerf thickness in m
$f = e + \lambda$
L_T: saw kerf length in m
d: log diameter in m
c: Saw kerf chord
e: thickness of a board in m

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- Calculation of edging volume

$$V_{de_2} = Np \cdot L_p \cdot l_p \cdot e_P \tag{9}$$

- Calculation of sawdust volume

$$V_{S_3} = L_T \cdot \lambda \cdot N_T \tag{10}$$

- Calculation of slab volume

$$v_{D_2} = V_{b_2} - \left(v_p + V_{S_2} + Vs_3 + V_{de_2}\right) \tag{11}$$

- Calculation of trimming cutoff volume

The trimming cutoff volume was measured in waste piles by applying a void coefficient (ε) of 25%. The void coefficient is an important measure to characterize materials in piles.

$$V_\epsilon = L_\epsilon \cdot l_\epsilon \cdot H_\epsilon . \varepsilon \tag{12}$$

V_ϵ: volume of the pile in m^3
l_ϵ: width of the pile in m
H_ϵ: height of the pile in m
L_ϵ: Length of the pile in m

Others characteristics of wood waste

- Humidity

The R6015 wood HumidiMeter with portable wood tips, including a temperature probe and a memory containing 8 wood groups with calibrations for 170 wood species, was used to measure wood waste humidity.

- Calorific value

The gross weight net calorific value (NCV) of a wood fuel can be estimated from its humidity and its anhydrous calorific value using Table 1.

Table 1. Calorific value according to humidity (Source: Eurobserver, 2005)

Humidity	20%	25%	30%	35%	40%	45%	50%	55%
NCV (kWh/T)	3 880	3 600	3 444	3 208	2 800	2 536	2 256	1 920

- Density and energy potential

The density of wood waste was considered similar to that of the wood from which it derived. Thus, the density of all the wood species processed in the wood processing unit (WPU) during the month of March was collected and their average calculated.

The energy contained in the deposit is a function of the calorific value of the wood waste, its humidity level, and the available and exploitable mass. The energy potential (Ep) of these waste is therefore the product of the mass of the deposit (Mrb) by the NCV.

$$E_p = Mrb \cdot NCV \tag{13}$$

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This mass is the product of the average density (d) of the processed wood by the available volume (V).

$$Mrb = d \cdot V \tag{14}$$

Design and implementation of the thermoelectric system

A thermoelectric system in the contemporary sense of the term is a system equipped with a furnace in which sawdust is burned, a radiator for heat dissipation and, a thermoelectric generator to directly convert heat into electricity. Regarding the design and construction of the thermoelectric system, the technical feasibility of the project was tested by constructing an experimental prototype in which the Peltier module operated as a generator thanks to the temperature difference generated between its two faces, thus creating a potential difference and a current at the output.

Technical design

To design the device, the finite element modelling method (FEM) was used with the software SOLIDWORKS, which allows the rapid design of precise models based on 3D modelling and components (Hervé, 2008).

Construction of the experimental prototype

The furnace has a square base of 28 cm x 28 cm and a height of 35 cm. The lid has a square base of 17 cm x 17 cm and a height of 2.5 cm. The box housing the radiator has a square base of 11cm x 11cm.

- A tape measure was used to measure and mark the exact dimensions on the wooden boards;
- A mitre saw was used to cut the pieces according to the marks;
- An electric sander with a medium gain was used to remove any irregularities and burrs on the edges of the cut boards;
- The four sides of the furnace were assembled with the tips and a smooth sheet of 8.75 m^2 was added on the four faces of the furnace towards the inside;
- The box containing the radiator was inserted into the lid and placed on the furnace;
- The entire device was sanded with a fine sander to obtain a smooth surface;
- For an additional protection and a long-lasting finish, a protective varnish was applied to the entire device.

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Monitoring of performance

- Temperature

The variation in temperature from the beginning to the end of the experiments was measured using a laser thermometer capable of measuring temperatures ranging from -30°C to 300°C.

- Seebeck Coefficient

In an open circuit formed by two different semiconductors, where one of the contacts between the materials is at a temperature Tc and the other at a temperature Tf (Tf < Tc), an electrical potential difference or electromotive force (e.m.f.) arises at the ends of the circuit according to Eq.15 (Sylvie, 2014).

$$\Delta V = \alpha AB.(Tc - Tf) \tag{15}$$

Since the electromotive force depends only on the temperatures of the two junctions, it was measured by separating the two semiconductors at one of the junctions and connecting the two ends obtained to a voltmeter. The proportionality coefficient (αAB) also known as the Seebeck coefficient (discovered in 1821) was determined in V°C^{-1} by linear regression of the curve of variation of electric potential (ΔV) as a function of temperature (ΔT).

- Current intensity

The current intensity of the thermoelectric system was measured using a multimeter connected in series with the LED bulb.

- Electrical power

The electrical power exchanged in the system (P), the current (I) flowing through it and the voltage (U) at its terminals are linked by the Eq.16.

$$P = U \cdot I \tag{16}$$

P: Power in watts (W); U: Voltage in volts (V); I: Current in amperes (A)

Estimation of the system's potential energy contribution and the associated costs

Estimation of energy requirements and current costs

- Electricity consumption

The production balance sheet was drawn up for the month of March 2024. The various items of equipment, appliances and processes consuming energy were identified and their energy requirements calculated. The energy consumption (E) of each component as a function of its rated power and operating time during the month was determined using Eq.17.

$$E = P \cdot t \tag{17}$$

P: Power in kW; t: Operating time in hours

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Total electricity consumption for the month of March 2024 was refined using bills for diesel used and ENEO electricity. This electricity consumption was then related to the total monthly volume of wood processed to determine the electricity of procession (E) in kWh/m³.

$$E = \frac{Total\ energy\ consumption\ in\ kWh}{Total\ volume\ of\ wood\ processed\ in\ \mathrm{m}^3} \tag{18}$$

- Current electricity production costs

Using the invoice amounts for total monthly electricity consumption and the monthly volume of timber processed, the average electricity cost of production was calculated in FCFA/kWh (Ec) and then in FCFA/m³ (Ec').

$$Ec = \frac{Total\ amount\ spent\ on\ energy\ in\ FCFA}{Total\ energy\ consumption\ in\ kWh} \tag{19}$$

$$Ec' = \frac{Total\ amount\ spent\ on\ energy\ in\ FCFA}{Total\ volume\ of\ wood\ processed\ in\ \mathrm{m}^3} \tag{20}$$

Estimation of the system's contribution to meeting the company's electricity needs and system costs

The monthly production balance enabled us to calculate, for the processing of 1 m³ of timber, the energy consumed, the quantity of wood waste obtained and the heat energy that could potentially be extracted (Ep). To estimate the system's electrical potential, an electrical efficiency of 9% was considered (Hung-Hsieh et al., 2013). The annual prospective analysis, taking into account the increase in volumes of wood processed at Dino & Fils SA over the last five years, was based on a conservative processing target of 35,000 m³/year of wood by 2025 (Table 2).

Table 2. Volumes of wood processed from 2020 to 2024 and projection for 2025

Year	2020	2021	2022	2023	2024	**2025**
Wood Processed (m^3)	26 653	27 234	30 058	32 170	34 015	**35 000**

The costs considered for the thermoelectric system are those relating to: (i) the initial investment (purchase, installation and commissioning of the various components) and (ii) operation (production, maintenance, monitoring). These costs are fixed and based on quotations obtained from major international suppliers present or represented in Cameroon and on the local socio-economic context. The total annual cost is the sum of the annual depreciation (the life of the system was considered to be 15 years) and the annual operating cost, to which contingencies of up to 10% were added. The cost of producing 1 kWh from the system (unit cost) was then calculated in FCFA/kWh.

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$$Unit\ cost = \frac{Total\ cost\ spent/year}{Total\ number\ kWh/year} \tag{21}$$

Results and Discussion

Characteristics of wood waste at Dino & Fils SA

During the month of March 2024, 5 131 m³ of log timber were processed to obtain 1 847 m³ of green sawn timber (finished product) for an equivalent of 3 284 m³ of wood waste (Eq.1-12). The production yield is 36%, which is close to the average annual yield of this WPU (35%) and that of processing units in the same category in Cameroon (30%) (Girard et al., 2003).

Four (04) types of waste were obtained: slabs (1 847 m³), sawdust (821 m³), edgings (541 m³) and trimmings cutoff (73 m³). They are the classical waste of primary wood processing unit (Crehay et al., 2004). The production line for this procession is shown in Figure 2.

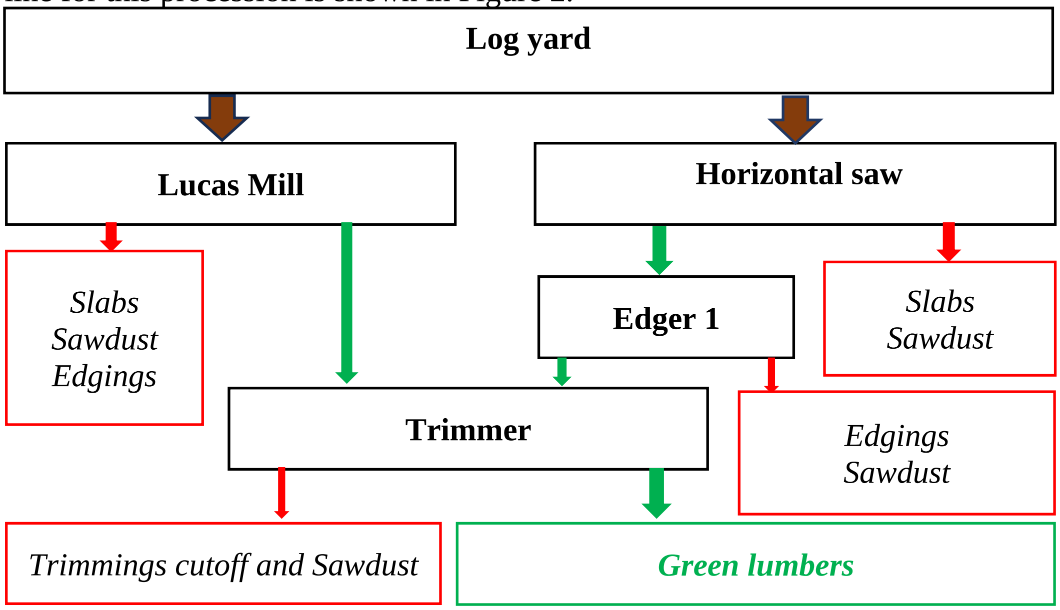

Figure 2. Production line of the primary level of processing at Dino & Fils SA

Considering the average density of all the wood processed in the WPU during the month of March (0.69 T/m³), the total mass of wood waste produced is therefore estimated at 2 266 T for an average volume of 3 284 m³ of waste (Eq. 14).

The average humidity of the species processed during the month of March 2024 is 40%, corresponding to a NCV of 2 800 kWh/T (Table 1). The wood waste produced on the site during the said month represent a calorific energy potential of 6 345 MWh (Eq. 13). Therefore, considering the electrical

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efficiency of the thermoelectric generator of 9%, the electrical potential of those wood waste is 571 MWh.

Table 3. Energy potential of wood waste

Parameters	Values
Volume of wood waste (m^3)	3 284
Average density (T/m^3)	0.69
Humidity (%)	40
NCV (kWh/T)	2 800
Mass (T/month)	2 266
Potential monthly heat energy (kWh)	6 344 800
Potential monthly electrical energy (kWh)	**571 032**

Experimental thermoelectric system

Presentation of prototype

Figures 3 and 4 show the system designed using SolidWorks software and the experimental prototype manufactured, respectively. The system consists of a wooden furnace with a smooth sheet metal inside in which sawdust is burnt. The radiator captures and dissipates the heat to the thermoelectric generator. The generator, on which the ice cubes are placed to create a temperature difference, converts the heat directly into electricity that makes the LED bulb in the cottage glow.

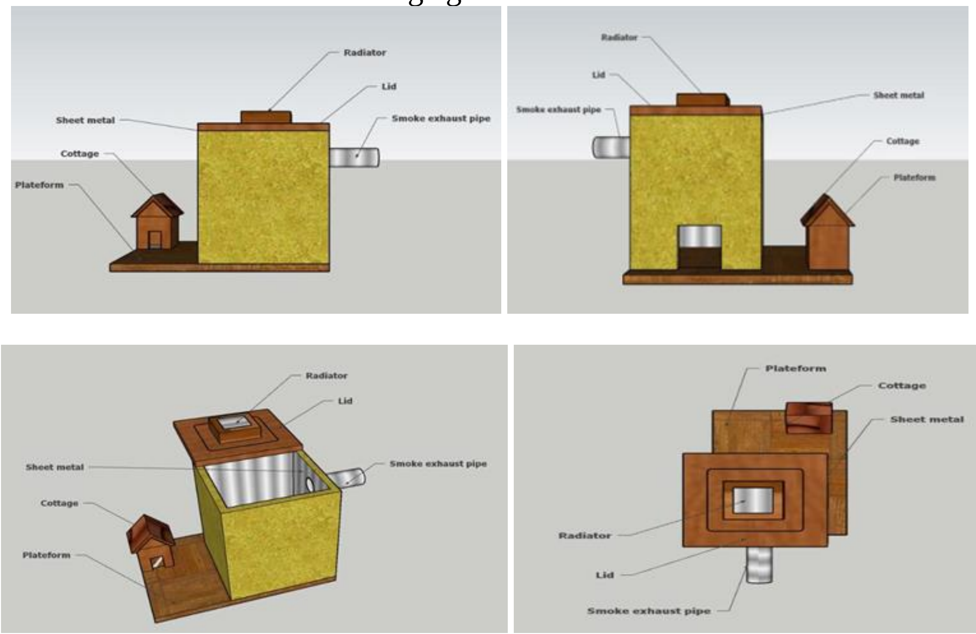

Figure 3. Designed thermoelectric system

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Figure 4. Manufactured thermoelectric system

Energy performance of prototype

The Peltier module functioned as an electromotive force generator resulting from the dissymmetry of the temperatures at the semiconductor junctions. The Seebeck coefficient obtained was 0.04 (Eq. 15), reflecting the fact that heat is converted into electricity (Fig. 5).

The LED bulb began to glow after 5 minutes of combustion at a temperature of 55°C; the current reading was 0.48 A, the voltage 2.3 V and the power 1.1 W (Eq. 16). The maximum power supplied by the system (25.9 W) was obtained at 185°C after 40 minutes of combustion (Fig. 6). The total power supplied during 85 minutes of combustion was 841 W, equivalent to 67% of the power that the system should supply under optimum conditions for 5 kg of sawdust placed in the furnace (1 260 W). This could be explained by the initial freshness of the sawdust (25°C), its high humidity (40%) and the fact that the furnace was open, resulting in significant heat loss.

However, the 6% efficiency is very encouraging as it is within the real efficiency range of applications using the Seebeck effect (5-9%) for the direct conversion of heat into electricity (Hung-Hsieh et al., 2013).

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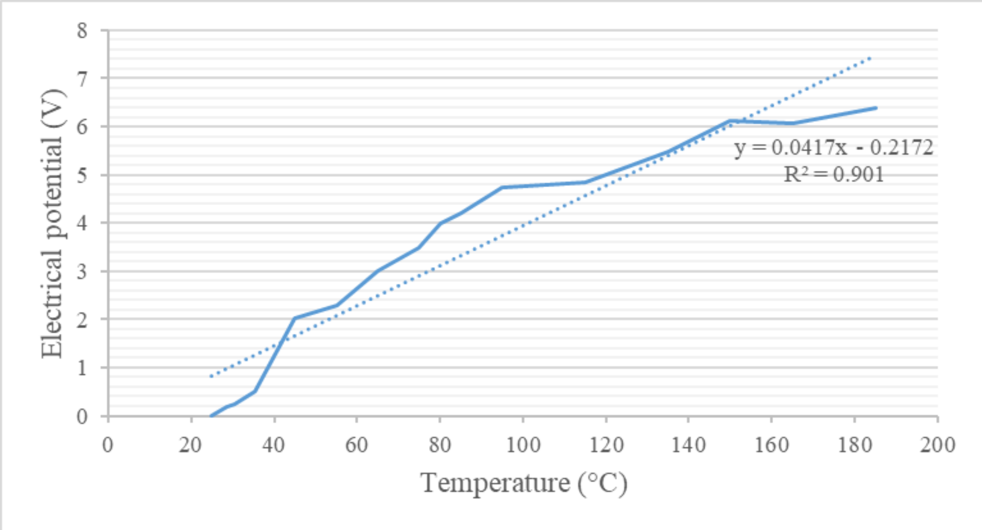

Figure 5. Variation of electrical potential as a function of temperature

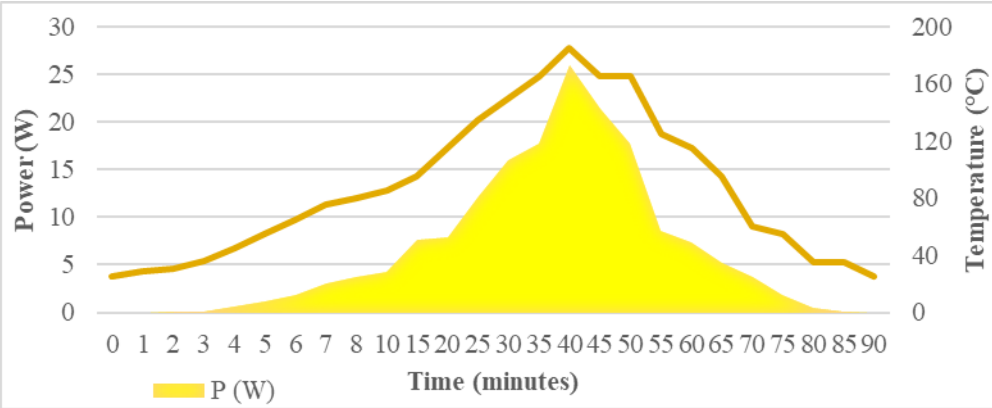

Figure 6. Variation of temperature and electrical power as a function of time

Potential energy contribution of the system and related costs

Current energy consumption and costs

During the month of March 2024, Dino & Fils SA consumed the equivalent of 121 334 kWh supplied by ENEO (98 283 kWh) and by the generator (23 051 kWh) to process 5 131 m^3 of wood. This is equivalent to an average energy consumption (E) of 24 kWh/m^3 of wood being processed (Eq. 18). Table 4 gives a breakdown of this consumption by workstation according to Equation 17.

Of the energy bills received for the month of March 2024, the rates applied are respectively 124 FCFA/kWh for ENEO and 237 FCFA/kWh for diesel (Table 5). With an average electricity cost (Ec) of 145 FCFA/kWh (Eq.

19), Dino & Fils SA is currently spending 3 439 FCFA/m^3 of wood being processed (Eq. 20).

Table 4. Breakdown of energy consumption by workstation

Services	Energy consumption of equipment (kWh)
Sharpening	1 305
Joinery	1 431
Production of glued slats	8 461
Sawmill	18 462
Dryer	33 609
Others consumptions (office automation, transport, logistics)	58 066
TOTAL	**121 334**

Table 5. Current electricity production costs

ENEO		**DIESEL**		**TOTAL**	
Consumption	Price	Consumption	Price	Consumption	Price
98 283 kWh	12 190 863 FCFA	23 051 kWh	5 453 208 FCFA	121 334 kWh	17 644 071 FCFA
Cost: 124 FCFA/kWh		**Cost: 237 FCFA/kWh**		**Average cost (Ec) : 145 FCFA/kWh**	

Potential energy contribution of the thermoelectric system and related costs

With an average processing rate of 30 000 m^3/year of wood over the last five years and a minimum projection of 35 000 m^3 from 2025 (Table 2) at an average yield of 35%, Dino & Fils SA would produce an average of 22 750 m^3 of wood waste annually, equivalent to 15 697 T in mass. The electrical potential of these waste is 3 956 MWh/year, or 113 kWh/m^3 of wood being processed, which is higher than the current consumption of 24 kWh/m^3. Therefore, by exploiting the electrical potential of its wood waste, Dino & Fils SA would be able to cover all its processing energy needs and could even consider diversifying its activities. The on-site installation of a thermoelectric power station running on wood waste would enable the company to free itself from current energy constraints and become self-sufficient.

The estimation of the costs of the system took into account the initial investment, based on a 15-year lifespan for the equipment, and operating costs. With annual expenditure (depreciation + annual operating costs) of 191 916 516 FCFA (Table 6), the system would produce 3 956 MWh annually, that is a unit cost of 48 FCFA/kWh (Eq. 21). This production cost, which is much lower than the current average cost of supplying electrical energy to Dino & Fils SA (145 FCFA/kWh), is very advantageous and very competitive for its positioning as a supplier of electrical energy to surrounding households and services in accordance with the national electricity policy (République du Cameroun, 2012).

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Table 6. Thermoelectric system costs

CAPITAL EXPENDITURE (I)			**505 043 400 FCFA**
I.1. Technical equipment			**423 043 400 FCFA**
Thermoelectric power station	Thermoelectric generator	357 216 800 FCFA	
	Cooling system	15 000 000 FCFA	
	Radiator	5 000 000 FCFA	
Boiler	Boiler	21 187 200 FCFA	
	Firefighting system	3 280 000 FCFA	
Grinding machine		8 059 400 FCFA	
Transformers		5 000 000 FCFA	
Chimney	Smoke treatment and evacuation	8 300 000 FCFA	
I.2. Small equipment		12 000 000 FCFA	**12 000 000 FCFA**
I.3. Logistics and installation			**70 000 000 FCFA**
Customs clearance and transport		50 000 000 FCFA	
Installation		20 000 000 FCFA	
OPERATING EXPENSES (II)			**140 800 000 FCFA/Y**
II.1. Staff			**37 200 000 FCFA**
1 Production manager	400 000 FCFA/month	4 800 000 FCFA	
1 Maintenance agent	300 000 FCFA/month	3 600 000 FCFA	
3 Grinding agents	3 x 200 000 FCFA/month	7 200 000 FCFA	
6 Loading agents	6 x 200 000 FCFA/month	14 400 000 FCFA	
2 Ignition/stop agents	2 x 150 000 FCFA/month	3 600 000 FCFA	
2 Ash removal agents	2 x 150 000 FCFA/month	3 600 000 FCFA	
II.2. Consumables and services			**103 600 000 FCFA**
Spare parts		50 000 000 FCFA	
Small tools		10 000 000 FCFA	
Small consumables	Glues, thermal paste…	21 600 000 FCFA	
Equipment maintenances	Welding, repairs	12 000 000 FCFA	
Control and regulation	Monitoring, control, audit…	10 000 000 FCFA	
ANNUAL EXPENDITURE (I'+II+III)			**191 916 516 FCFA**
DEPRECIATION (I' = I/15)		**33 669 560 FCFA**	
OPERATING EXPENSES (II)		**140 800 000 FCFA**	
CONTINGENCIES [III = 10%(I'+II)]		**17 446 956 FCFA**	

Conclusion

Wood waste account for 64% of all the wood processed at Dino & Fils SA. With their good characteristics and thermoelectric potential, this make them an interesting and directly available source for sustainable energy recovery.

The design and implementation of an experimental protocol has made it possible to apply the Seebeck effect and prove that it is possible to produce electricity from these wood waste. With an experimental electrical efficiency of 6%, the system has been proved to be effective and promises better performance on a real scale and under optimum conditions.

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The installation and operation of a thermoelectric system at Dino & Fils SA would enable it to fully meet its energy needs at a beneficial cost of 48 FCFA/kWh instead of the 124 FCFA/kWh currently spent. It would also enable the company to expand or diversify its activities by adding a production line and/or positioning itself as a local electricity supplier to surrounding households and offices.

Although thermoelectric systems have a relatively low efficiency compared with other energy conversion technologies, such as gas or steam turbines, this does not mean that their use should be completely ruled out. In order to optimize the thermoelectric efficiency of the experimental system, it would be wise to add a system for channelling hot smoke and reinjecting them at the head of the system in order to dry and preheat the sawdust before actual combustion in the furnace. This furnace should also be as airtight as possible to prevent heat loss, which would have a negative impact on process efficiency.

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