International Journal of Multidisciplinary and Current Educational Research (IJMCER)
ISSN: 2581-7027 ||Volume|| 6 ||Issue|| 4 ||Pages 232-240 ||2024||

Environmental and energy optimization of stills in Nosy-Be: transition to sustainable photovoltaic systems

[1,]RAZAFIMANDIMBY Fabrice, [2,]Jean Claude RAKOTOARISOA,
[3,]RAKOTONIRIANA Jimmy Bona Michel, [4,]Jean Nirinarison RAZAFINJAKA
[1]Thematic Doctoral School of Renewable Energy and Environment, University of Antsiranana,
[2]Automation Laboratory, Higher Polytechnic School, University of Antsiranana,
[3]Laboratory of Electrical Machines, Higher Polytechnic School, University of Antsiranana.

ABSTRACT : In Nosy-Be, many stills still run on wood, a traditional method leading to environmental consequences such as deforestation and CO2 emissions. This study compares the wood consumption and CO2 emissions of three types of 1600 kg stills: electric, steam generator, and simple, using linear regression analysis to assess the impact of distillation capacity and oil yield. The results demonstrate that the electric still, which does not require wood, presents a significant environmental advantage, while larger capacity stills consume more wood and emit more CO2. To optimize photovoltaic systems, a direct calculation sizing method with loss factors was used. Simulations with PVsyst revealed an initial investment of 4,759,266,917 Ar, annual expenses of 76,500,000 Ar, an energy cost of 625,084 Ar, a cumulative profit of 6,721,101,000 Ar and a payback period of 14.7 years. The electric still is thus promoted as the most environmentally friendly solution. Using Critical Pathway (CPM) and Program Evaluation and Review (PERT) methods, this study also made it possible to effectively plan the transition to electric stills and photovoltaic systems, optimizing operations to minimize delays and the costs.

KEYWORDS – environmental impact, stills, photovoltaic systems, optimization.

I. INTRODUCTION

The distillation of ylang-ylang essential oil is an important economic activity on Nosy-Be, an island in northwest Madagascar. However, the traditional method using wood-fired stills [1] causes major environmental problems, including deforestation, loss of biodiversity and soil erosion, thereby contributing to climate change. The oldest known distillation device, dating from 3500 BC, was discovered in Mesopotamia (present-day Iraq) [2]. The consumption of wood for these stills results in CO_2 emissions proportional to their capacity and their cooking time.

Before producing ylang-ylang oil, several steps and conditions must be respected [3], [4]. This study proposes to optimize the sizing of a photovoltaic system to power the stills, with the aim of reducing their environmental impact and improving their energy efficiency. Photovoltaic systems, as renewable energy sources, offer a sustainable alternative to traditional methods [5].The transition to photovoltaic systems has several advantages: reducing dependence on wood, reducing CO_2 emissions and exploiting a sustainable energy source adapted to the sunny conditions of Nosy-Be. This study compares wood consumption and CO_2 emissions associated with three types of stills: electric, steam generator, and wood. We used linear regression [6] to model the relationships between distillation capacity, oil yield, wood consumption and CO_2 emissions, with the aim of optimizing still performance.

Photovoltaic systems were sized by direct calculation by integrating the losses [7], in order to determine the necessary power of the solar panels and batteries. Then, the PVsyst software was chosen for sizing due to its ability to simulate photovoltaic systems accurately, taking into account solar data and energy needs, and to provide a detailed analysis of performance and profitability economics of the projects, the results obtained show that the transition from wood stills to electric stills powered by photovoltaic systems could significantly reduce wood consumption and CO_2 emissions in Nosy-Be. To illustrate this approach, we conducted a comparative study with a 1600 kg still requiring 120 kW, based on real data from five stills of different sizes. The energy required for the still depends on its capacity. CPM and PERT methods were used to identify critical tasks, estimate activity durations despite uncertainties, and optimize resource and schedule management to ensure an efficient transition to sustainable technologies while minimizing environmental impacts.

II. OPERATING PRINCIPLE OF A DISTILLER

There are several types of stills, but their operating principle is the same depending on the steam. A still is a device used to obtain essential oils, initially used to make perfumes, essences or pharmaceutical products [8], [9], [10]. It consists of four main parts: the body or boiler, which contains the liquid to be distilled and is placed in the bain-marie or directly on the hearth; the capital, which covers the body and is provided with a column where the vapors rise; the swan neck, a cylindrical tube that conducts the vapors to the condenser; and finally the condenser or coil, a helical tube where the vapors condense thanks to the liquid circulating around [11].

Figure 1: Simple still made from wood in Nosy-Be

Figure 2: Steam engine powered by dry wood

III. METHOD AND MATERIAL

Description of data and calculation methods : To evaluate the performance of the stills in Nosy-Be, an on-site survey was carried out to collect data on oil yield, wood consumption, and CO_2 emissions for different still capacities. Wood consumption data were converted to costs in euros using a fictitious exchange rate of €1 = 4000 Ar, and CO_2 emissions were calculated based on an average emission value of 0.74 kg CO_2 per m^3 of wood burned. The methods used for these calculations are described in detail below.

Environmental assessment of stills: simple, AGV and electric : Our comparative study concerns three types of 1,600 kg stills (having the same capacity, but different power supply modes): the simple wood still, the steam generator still (AGV) and the still electric. The objective is to evaluate their energy efficiency and their environmental impact. Energy and wood consumption calculations for each type of still were carried out using the following formulas:

$$E(kWh) = P_m(kW) \times T(hours) \qquad (1)$$

This formula means that the total energy consumed (E) is equal to the average power of the still (Pm) multiplied by the operating time (T).

$$B_C(kg) = \frac{E(kwh)}{E_a(kwh/_{kg}) \times R} \qquad (2)$$

B_C represents the wood consumption, Ea is the specific energy of the wood, and R is the wood yield. This method makes it possible to quantify wood consumption based on the energy required for distillation, taking into account the power of the still and the efficiency of wood as an energy source. Data for the power and cooking time of each type of still was collected and used in these formulas to assess the energy efficiency and environmental impact of the distillation process.

Linear regression model with two dependent variables: To build the linear regression model [12], we first need to examine the relationships between the capacity of each still, oil yield, wood consumption and CO2 emissions. Next, we apply the least squares method to fit a straight line to our data. This method makes it possible to estimate the model coefficients from the data provided. Once the coefficients are estimated, the model can be used to predict wood consumption and CO2 emissions for the five stills.

1. We assume a model of the form

$$\begin{cases} \beta = \beta_{0B} + \beta_{1B}C + \beta_{2B}R + \in_B \\ CO2 = \beta_{0co2} + \beta_{1co2}C + \beta_{2co2}R + \in_{CO2} \end{cases} \tag{3}$$

Or

β_{0B} is the intercept for wood consumption.

β_{1B} and β_{2B} are the regression coefficients for wood consumption versus C and R respectively.

β_{0CO2} is the intercept for CO2 emission.

β_{1CO2} and β_2CO2 are the regression coefficients for CO2 emission with respect to C and R respectively.

$\in_B$ and ∈_$\in_{CO2}$are the residual errors.

Calculation of regression coefficients : To estimate the coefficients, we use the least squares method, which solves the system of normal equations for each dependent variable [13], [14], [15].

2. For wood consumption (B)

$$\begin{bmatrix} n & \sum C_i & \sum R_i \\ \sum C_i & \sum C_i^2 & \sum C_i R_i \\ \sum R_i & \sum C_i R_i & \sum R_i^2 \end{bmatrix} \begin{bmatrix} \beta_{0B} \\ \beta_{1B} \\ \beta_{2B} \end{bmatrix} = \begin{bmatrix} \sum B_i \\ \sum C_i B_i \\ \sum R_i B_i \end{bmatrix} \tag{4}$$

3. For the emission of CO2 (CO2)

$$\begin{bmatrix} n & \sum C_i & \sum R_i \\ \sum C_i & \sum C_i^2 & \sum C_i R_i \\ \sum R_i & \sum C_i R_i & \sum R_i^2 \end{bmatrix} \begin{bmatrix} \beta_{0CO2} \\ \beta_{1CO2} \\ \beta_{2CO2} \end{bmatrix} = \begin{bmatrix} \sum C_i \\ \sum C_i CO2_i \\ \sum R_i CO2_i \end{bmatrix} \tag{5}$$

A. Photovoltaic Sizing Methods

The photovoltaic system sizing method is based on direct calculation with loss factors to determine the necessary power of solar panels and batteries. It includes the following steps:

1. Calculation of Peak Power (Pc)

The peak power is calculated according to the daily requirement (Bj) and the daily sunshine (Eensol.j), with a loss factor (Kp):

$$P_c = \frac{B_j}{E_{ensol.j} \times K_p} \tag{6}$$

2. Number of Modules

The number of modules required (nm) is calculated by dividing the peak power by the unit power of a module (Pm):

$$n_m = \frac{P_c}{P_m} \tag{7}$$

3. Capacity of the Storage System

The necessary battery capacity (Cbatt) is determined by multiplying the electricity consumption in Ah by the desired autonomy duration, then applying a safety coefficient [16]:

$$C_{batt} = \frac{B_j \times Autonomy}{U_{Syst} \times D_d \times n_{ond}} \tag{9}$$

4. Number of Batteries

The number of batteries in series (Nbs) and in parallel (Nbp) is calculated based on the system voltage and the unit capacity of the battery:

$$N_{bs} = \frac{U_{syst}}{U_{batt}} \tag{10}$$

$$N_{bp} = \frac{C_{batt}}{C_U} \tag{11}$$

5. Sizing of the Inverter

The number of inverters required (no$_{nd}$) is calculated based on the peak power and the power of the inverter:

$$n_{ond} = \frac{P_c}{P_{ond}} \tag{13}$$

B. Simulation Methods and Performance Analysis

PVsyst is advanced simulation software used for the sizing and optimization of photovoltaic systems. This software allows you to:

- Define energy needs.
- Select photovoltaic modules and inverters.
- Perform simulations to evaluate different system configurations.

PVsyst offers tools to simulate stand-alone or hybrid photovoltaic systems, using precise solar data and energy needs to create varied simulation scenarios. Users can analyze system performance, adjust configurations based on the results obtained, and evaluate the economic profitability of projects by calculating investment costs, operating costs, energy costs and cumulative profit.

Planning Key Steps for the Transition towards Electric Stills in Nosy-Be

1. Planning Method and Necessary Material : To plan the key steps of the transition to electric stills in Nosy-Be, the Critical Path Methods (CPM) and Program Evaluation and Review Methods (PERT) were used. These methods allow to optimize operations and minimize delays by taking into account the optimistic, probable and pessimistic durations of the activities. Key activities include the purchase of equipment, the installation of solar panels, the integration of the photovoltaic (PV) system and commissioning tests.

IV. RESULTS AND DISCUSSION

Performance of Stills : Table 1 presents the data collected regarding the performance of stills of different capacities, including oil yield, cooking time, wood consumption, CO_2 emissions, and wood cost. The results show that oil yield and wood consumption increase with still capacity, while cooking time remains relatively stable for capacities above 200 kg. CO_2 emissions also increase with capacity, highlighting an increasing environmental impact for larger stills.

Table 1: Still performance data for different capacities

Capacity (kg)	Oil yield (kg)	Cooking time (hours)	Wood consumption (m^3)	Co$_2$ em0issions (kg)	Cost of wood (euros)
50	1,5 - 2	16 - 24	1,5 - 2	1,1 - 1,5	7,5 - 10
100	2,5 - 3	18 - 24	2 - 3	1,5 - 2,2	10 - 15
200	5 - 6	20 - 24	5 - 6	3,7 - 4,4	25 - 30
400	10,5 - 12	20 - 24	5 - 8	3,7 - 5,9	25 - 40
1600	40 - 46	30 - 36	40 - 48	29,6 - 35,7	200 - 240

The table above indicates that larger stills, although offering a higher oil yield, also have significantly higher wood consumption and CO_2 emissions. These factors highlight the increased environmental impact associated with the use of larger capacity stills.

Distillation Time Analysis : Table 2 compares the distillation time needed for different types of stills. The results show that smaller stills have shorter distillation times due to their smaller volume, while larger stills require more time due to their larger capacity. These variations influence the performance and operational costs associated with each type of still.

Table 2: Comparison of distillation times for different still sizes

Still Size	Capacity (kg)	Distillation Time (hours)
Little	10	4-6
AVERAGE	50	8-12
Big	100 +	12-24

The distillation time increases with the size of the still, although this time remains relatively constant for large capacity stills. Smaller stills offer faster distillation cycles, but may require multiple cycles to process large quantities. The results indicate that the size of the stills significantly influences oil yield, wood consumption, CO_2 emissions, and distillation time. Large stills, while efficient at processing large quantities of material in one go, incur higher environmental costs due to their increased wood consumption and CO_2 emissions. Smaller stills, although requiring multiple cycles to process large volumes, have a lower environmental impact and reduced operational costs. By structuring information in this way, you provide a clear, detailed view of the performance and environmental impact of different types of stills, while integrating the data and analytics needed for a thorough understanding

Comparison of Energy Consumption and Environmental Impacts of Stills : The results show that stills have different energy consumption and environmental impacts depending on their power mode. Simple stills, with an average power of 2,454 kW and a cooking time of 36 hours, consume a lot of wood. Steam generator stills (AGV), although fewer in number, are more energy efficient with a power of 3,212 kW and a cooking time of 12 hours, thus reducing their wood consumption. Electric stills, although non-existent on the island, stand out for their zero wood consumption, a power of 120 kWh and a cooking time of 12 hours.

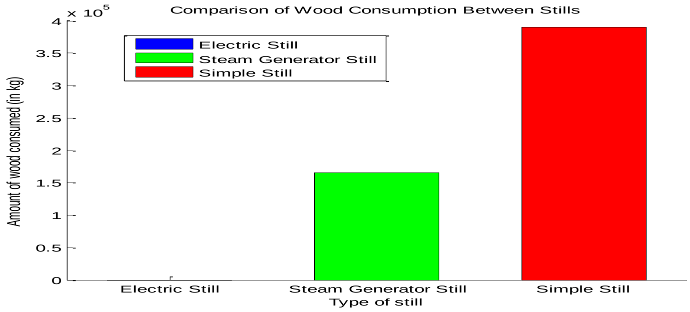


Figure 3: Comparative analysis of wood consumption between electric, steam generator and simple stills

The fig. 3 shows a histogram comparing the quantity of wood consumed by three types of stills: the electric still, the steam generator still, and the simple still. The bars are colored differently: blue for the electric still, green for the steam generator still, and red for the simple still. The blue bar represents the electric still, which does not consume wood [17], highlighting its significant environmental advantage. On the other hand, the green bar of the steam generator and the red bar of the simple still show that they consume a notable amount of wood. This comparison highlights that stills do not consume the same amount of wood, with the electric still standing out as the most environmentally friendly.

Wood Consumption and CO2 Emissions

Table 3: Presents fictitious data used to illustrate the regression model.

Capacity (C)	Oil yield (R)	Relative yield	Wood consumption (B)	CO2 emissions (CO2)
50 kg	1.75 kg	3,5%	1.75 m^3	2.5 kg
100 kg	2.75 kg	2,75%	2.5 m^3	3.5 kg
200 kg	5.5 kg	2,75%	5.5 m^3	7.5 kg
400 kg	11.25 kg	2,8125%	6.5 m^3	9.0 kg
1600 kg	43 kg	2,6875%	44 m^3	60.0 kg

Oil yield: The amount of oil obtained (in kg).

Relative yield: The proportion of raw material converted into oil (in %).

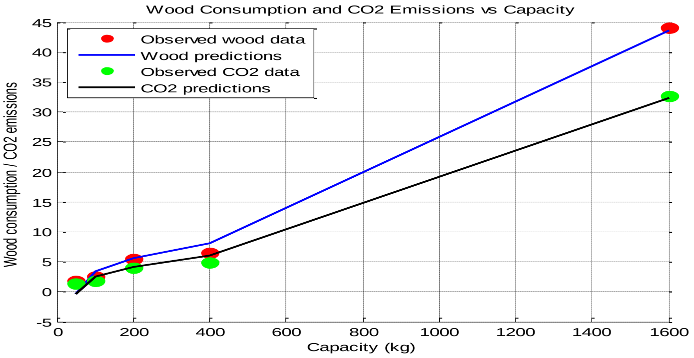


Figure 4: Analysis of Wood Consumption and CO2 Emissions as a Function of Still Capacity and Yield

Fig.4 shows the relationships between the capacity of the stills, their oil yield, and two variables: wood consumption and CO2 emissions. The curves illustrate how predictions based on a regression model compare to observed data for these two criteria. The results show that larger capacity stills consume significantly more wood and emit more CO2, while stills with higher oil yield consume less wood and emit less CO2. This method allows these relationships to be quantified and highlights the importance of optimizing stills to reduce deforestation and greenhouse gas emissions, highlighting the major environmental problem associated with the use of wood-fired stills. The regression coefficients obtained for wood consumption (B) and CO2 emissions reveal significant relationships between these variables and the factors of capacity and oil yield. For wood consumption, the constant coefficient is 1.1775, indicating wood consumption when capacity and oil yield are zero. The coefficient of 0.2214 shows that wood consumption increases by 0.2214 m³ for each additional kilogram of capacity, while the coefficient of -7.2526 reveals a decrease of 7.2526 m³ of wood for each additional kilogram of oil yield. For CO2 emissions, the constant coefficient is 0.8604, representing CO2 emissions without capacity or oil yield. The coefficient of 0.1644 indicates an increase of 0.1644 kg of CO2 for each additional kilogram of capacity, while the coefficient of -5.3867 shows a reduction of 5.3867 kg of CO2 for each additional kilogram of oil yield.

The importance of this method lies in its ability to quantify the impact of different factors on resource consumption and greenhouse gas emissions, thus allowing informed decisions to be made to improve energy efficiency and reduce the carbon footprint of industrial processes.

Calculations and Sizing : The values calculated for the sizing of the photovoltaic system are presented in the following table:

Table 5: Table of values to calculate

Element	Calculated value
Peak Power (Pc)	315,79 kWc
Number of Modules	1053
Serial Modules	19 à 22 panels
Parallel module	48 panels
Battery Capacity	77320 Ah
Batteries in Series	8
Batteries in Parallel	30
Total Number of Batteries	240
System Voltage	48 V
Number of Inverters	5
Number of Inverter Chargers	15
Box Multi-Cluster	Suitable for 15 inverters

The photovoltaic sizing method by direct calculation with loss factors made it possible to precisely determine the power and storage requirements to power a 1600 kg still with a 120 kW steam generator. The results show that for a daily consumption of 1440 kWh with sunshine of 6 kWh/m²/day, it is necessary to have 315.79 kWp of peak power, obtained by the use of 1053 photovoltaic modules of 300 W each. In terms of storage, the battery capacity must be 77320 Ah, requiring a total of 240 batteries configured in 8 series of 30 parallels to maintain a system voltage of 48 V. Sizing of the inverters reveals that 5 inverters of 60 kW each and 15 charger inverters for efficient energy management. This method ensures optimal operation of the photovoltaic system by taking into account various potential losses and optimizing the use of available resources. The results obtained highlight the importance of accuracy in calculating energy requirements and hardware configurations to ensure stable and efficient power supply to the system [18].

Simulation results with PVsyst

In a typical simulation carried out with PVsyst, the results obtained are as follows: The results show how PVsyst helps design cost- and performance-efficient photovoltaic systems. For example, a total investment of 4,759,266,917 Ar with an annual expenditure of 76,500,000 Ar makes it possible to achieve an energy cost of 625,084 Ar per kilowatt hour. The cumulative profit over the amortization period of 14.7 years is 6,721,101,000 Ar, which demonstrates significant economic profitability of the project.

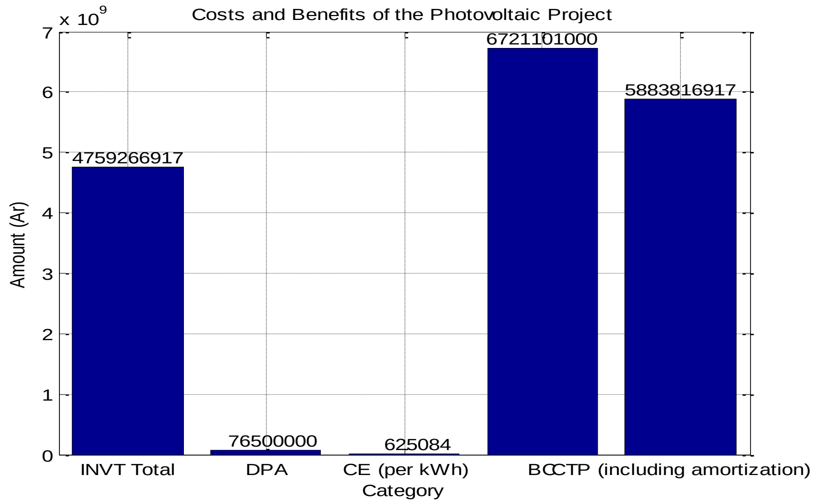


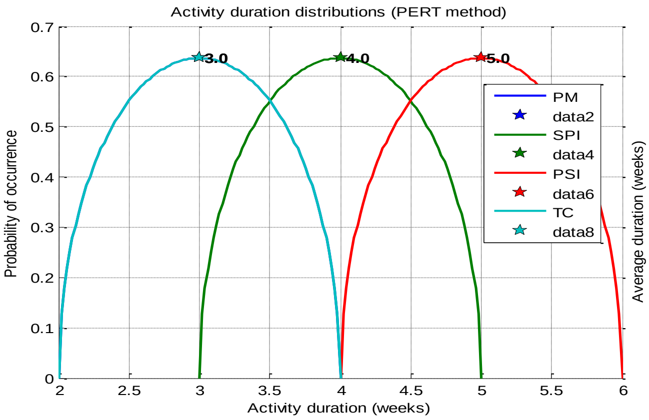
Figure 5 illustrates the different financial aspects of the photovoltaic project

The financial analysis of the project reveals that the total investment (INVT Total) represents the initial amount invested, while the annual expenditure (DPA) includes the recurring operating and maintenance costs. The cost of energy per kilowatt hour (CE) indicates the cost of producing energy, and the cumulative benefit (BC) reflects the gains generated by the system over the amortization period. Finally, the total project cost (TCC) includes all expenses and amortization over a period of 14.7 years. Visualization makes it possible to compare and understand the overall impact of the different financial components of the project. In general, the cost of the project is high, but it has advantages over the traditional still, where the cost of wood to the still location is 20 000 Ar per cubic meter, and the wood supply can sometimes be difficult.

Duration of Activities with the PERT Method : The calculation of the average duration for each activity is carried out using the PERT formula [19], [20]:

$$t_e = \frac{O+4M+P}{6} \qquad (15)$$

- O: optimistic duration of the activity
- M: most likely duration of the activity
- P: pessimistic duration of the activity
- t_e: average duration of the activity



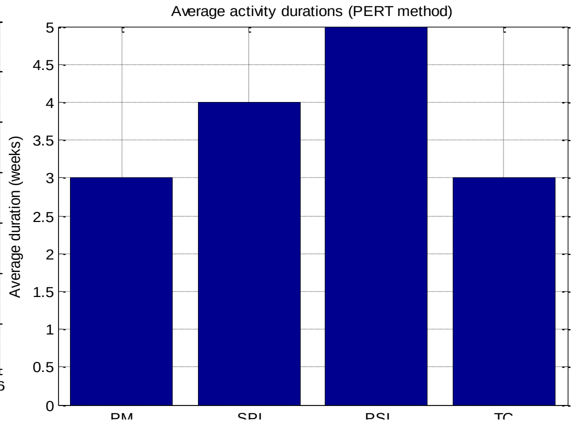


Figure 6: Activity Duration Distributions

Figure 7: Average Duration of Activities (PERT Method)

Fig.6 shows the activity duration distributions using the PERT method. For example, for the material purchase (MA) activity, the optimistic duration is 2 weeks, the most likely duration is 3 weeks, and the pessimistic

Duration is 4 weeks. Solar panel installation (IPS) has an optimistic duration of 3 weeks, a most likely duration of 4 weeks, and a pessimistic duration of 5 weeks. PV system integration (ISP) has an optimistic duration of 4 weeks, a most likely duration of 5 weeks, and a pessimistic duration of 6 weeks. Finally, testing and commissioning (TMS) has an optimistic duration of 2 weeks, a most likely duration of 3 weeks, and a pessimistic duration of 4 weeks. Fig.7 shows the average durations calculated for each project activity using the PERT method. Material procurement (MP) takes an average of 3 weeks. Solar panel installation (IPS) has an average duration of 4.33 weeks. PV system integration (ISP) requires an average of 5.67 weeks. Testing and commissioning (TMS) takes an average of 3 weeks.These average durations make it possible to plan the project taking into account uncertainties and to estimate the total duration of the project by identifying the critical path. Duration distributions show the uncertainties associated with each activity, allowing you to identify the most likely durations and better manage project risks and deadlines.Using CPM and PERT methods, key stages of the transition to electric stills in Nosy-Be can be planned efficiently, thereby minimizing delays and optimizing operations. The results show that, despite the uncertainties, the average activity durations allow a realistic and manageable estimate of the total project duration.

V. CONCLUSION

In conclusion, this study demonstrates that the transition to electric stills powered by photovoltaic systems constitutes the most environmentally friendly solution for the distillation of ylang-ylang essential oil in Nosy-Be. Thanks to the comparative analysis of the wood consumption and CO_2 emissions of three types of stills (electric, steam generator, and simple), the significant environmental impact of traditional methods was highlighted. Using linear regression to evaluate relationships between distillation capacity, oil yield, wood consumption and CO_2 emissions allowed still performance to be modeled and optimized.Simulations carried out with PVsyst showed that an initial investment of 4,759,266,917 Ar, accompanied by annual expenses of 76,500,000 Ar, led to an energy cost of 625,084 Ar. With a cumulative profit of 6,721, 101,000 Ar and a payback period of 14.7 years, the adoption of photovoltaic systems offers substantial economic benefits. In addition, the integration of loss factors in the sizing of solar panels and batteries made it possible to guarantee the reliability and efficiency of the proposed energy systems.

Additionally, Critical Pathway (CPM) and Program Evaluation and Review (PERT) methods were crucial to effectively planning the transition to electric stills and photovoltaic systems. These methods made it possible to identify critical tasks, estimate the duration of activities despite uncertainties, and optimize resource and schedule management. By minimizing delays and costs, we ensured efficient implementation of new technologies, while reducing the environmental impact of distillation activities in Nosy-Be.Thus, this study confirms that the adoption of electric stills powered by photovoltaic systems is not only economically viable, but also beneficial for the environment, constituting an important step towards sustainable and responsible production of essential oil ylang-ylang.

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