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Research Article

# Hybrid Renewable Energy Supply System for Remote Villages of Grid in Madagascar Using Linear Programming by Simplex Method and Genetic Algorithms

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## Abstract

This paper details the development of a linear model to optimize the sizing of a hybrid renewable energy supply system (HRESS) for remote rural villages in developing countries. The model studied is defined by its energy supply versatility to rural household consumers. It includes electrical energy, thermal energy for cooking, and also muscular energy used for transport and manual work related to the HRESS and agriculture. For HRESS design, the approach optimizes the objective function related to total annual cost. Our optimization methodology is organized around simplex and genetic algorithms. They are simple to implement and compatible with linear programming. First, we use the deterministic simplex method for model design; second, we use a genetic algorithm as a heuristic to optimize the multi-criteria objective function. The simplex method yields a solution based on weighting coefficients $\alpha$ for cost, $\beta$: for $CO_2$ emissions, *and* $\gamma$: for renewable energy sources. Our approach provides a three-dimensional Pareto front (total cost, $CO_2$ emissions, and share of renewable sources). To demonstrate the design process of HRESS, a numerical study is drawn from the fishing village of Lavanono, located in the extreme south of Madagascar. In the context of minimizing total cost Z, the single economic-criterion method demonstrates a preference for non-renewable energy sources. Specifically, the implementation of the simplex and genetic algorithm methods results in the selection of diesel generators for 100% of the electricity supply, with a production of 128,551 kWh, and firewood for 100% of the energy for cooking, with a production of 379,600kWh. The novelty of our approach lies in the integration of human and animal muscle power into the HRESS. The optimization of this approach yields 12 workers (1,382 kWh) and 10 beef domestic power (5,760 kWh) in the HRESS. The aforementioned amount is equivalent to Z=38,052 USD. The three-dimensional Pareto front is utilized to achieve a sustainable HRESS. The intermediate compromise is as follows: an 80% share of renewable energy sources: agrivoltaics, wind, and biogas. Agrivoltaics and wind power together provide 80% of the electricity supply. The diesel generator supplies the remaining 20%. It is estimated that biogas accounts for approximately 40% of clean cooking in the village of Lavanono. The emission limit of HRESS is set at 150 tons of carbon dioxide per year. In this case, the total cost of the project becomes Z = 70,500 USD.

## Keywords

Off-grid Electrification, Hybrid Energy, Linear Programming, Genetic Algorithm

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# 1. Introduction

Actually, the economic well-being and the quality of life are closely related to the availability of energy. The use of even small quantities of energy in the rural areas of Madagascar could be a good start towards the path leading to the solution of the problems of electrification.

The current electrification rate is around 35%, while access to clean cooking appliances is much lower, reaching only 5% of Malagasy households [1]. These low coverage rates are more pronounced in rural and remote areas.

In 2019, per capita electricity consumption in Madagascar was 74.1 kWh, the lowest in the world [2]. The national electricity and water company of Madagascar, JIRAMA (Jiro sy Rano Malagasy), is responsible for electricity generation, transportation, and distribution, and is currently experiencing significant challenges in its energy portfolio, with a heavy reliance on imported oil.

In 2024, JIRAMA's power plants produced 1,984,011 MWh, with 45.80% from thermal power plants, 47.90% from hydroelectric power plants, 4% from solar power plants, and 2.30% from hybrid solar/diesel power plants [3]. Madagascar has recently implemented a New Electricity Policy (NPE 2015-2030) with the ambitious target of providing electricity to 70% of households and achieving an energy mix composed of 80% renewable energy by 2030 [4].

To start the agroecological transition in Madagascar, the Malagasy agricultural production system is expected to evolve towards an agriculture that is more respectful of resources and the environment. The lack of conventional energy supplies and the irresponsible exploitation of natural resources has resulted in a substantial increase in deforestation on a large scale in Madagascar [5]. Other constraints that limit the development of Malagasy agricultural production: weakness of human capital, insufficiency and degradation of production and communication infrastructures, access to land, low use of fertilizers and improved production techniques, lack of energy infrastructure, road and adequate services. Remote rural areas of Madagascar do not have and are not expected to have electric grid supply in the near future. It appears that harnessing locally available renewable resources to supply the energy needs of remote rural areas is an option of energy planners.

Seaside and nautical tourism sector is an essential economic pillar in Madagascar [6]. It generates direct benefits for local communities, particularly those in the most isolated areas.

In rural area, design of stand-alone hybrid solar, wind and biogas plant have received the attention of researchers [7-12]. A few hybrid solar wind and biogas plants are operating around the world. In this article, we formulate the hypothesis, by mobilizing the contributions of muscular forces. The present study is based on the decentralized option for the energization off-grid of a cluster of isolated villages of one region in Madagascar.

# 2. Problem Description

In developing countries, farm power is an important resource for agriculture and at the same time agriculture is a resource for farm power [12]. Energy is an essential input in agriculture for increasing the production and productivity of the land.

To develop agriculture in remote rural villages, it is necessary to exploit the farm power for operating different types of jobs like tillage, planting and other stationary jobs like operating biogas, agriphotovoltaic (Agri-PV), wind plants, irrigation equipment, muscular power traction and motorized traction.

The economic-mathematical model of hybrid renewable energy system is formulated in the form of an optimization parameters bellows [7, 13]: surface of the Agri-PV plant in $m^2$, volume of biogas in $m^3$ per year, surface of propeller of the rotor of the wind power plant in $m^2$, Quantity of diesel for generator, Capacity of storage battery, number of solar cooker, number of manpower, number of animal labor, and quantity of organic fertilizer in ton per year.

Manual labor and animal traction in rural energification contribute to creating local jobs, training young people and raising awareness in the transition to more sustainable and resilient energy systems in rural remote areas. The method involves the minimization of an annual cost function subject to a set of constraints using a linear programming algorithm and Genetic algorithm. To evaluate the most economical solution, it is necessary to determine the optimal size of the installation.

# 3. The Model of the Components of Hybrid Renewable Energy Supply System (HRESS)

## 3.1. Model of Output of Solar Agri-PV

Solar energy is a renewable free and clean source of energy that is sustainable and totally inexhaustible at the human time scale. Solar rays produce electricity directly in photovoltaic cells without producing $CO_2$ or toxic waste. Agriphotovoltaic means Agriculture and photovoltaic, producing a volts. The Agri-PV combines the production of electrical energy and agriculture. An Agri-PV solar plant enables the dual use of agricultural land [14, 15].

In the context of climate change, solar panels protect cutures against severe climatic hazards such as drought, heavy rain, heat waves and hail. The shade provided by solar panels takes the strain off crops, farmes and livestock.

The output power of solar module at time **t** is defined by following formula [13]:

$$P_{APV}(t) = P_{STC} f_{dr} \left\{ \frac{G(t)}{1000} [1 + \alpha (T_c - 25)] \right\} \quad (1)$$

Where:

$P_{STC}$; power in Standard Test conditioning,
$f_{dr}$; derating factor,
α; temperature coefficient,
$T_C$; cell temperature.
Linear model of output power of agrivoltaic

$$P_{APV} = AG\eta_{APV} \quad (2)$$

Where; A, solar module surface in [m$^2$],
G; solar average irradiation in [W/m$^2$],
$\eta_{pv}$; solar module efficiency.

$$P_{Totpv}(t) = P_{pv}(t)N_{pv} \quad (3)$$

## 3.2. Model of Output Power of Wind Turbine

Wind energy comes from atmospheric changes. The changes in temperature and pressure make the air move around the surface of the earth. Wind power is a clean energy source that consist in converting wind energy into electricity by using wind turbines. A wind turbine creates pollution free energy. It is affordable, clean and sustainable. The linear power output of wind generator is as follows [16]

$$P_{wind} = \frac{1}{2}\rho AV^3 \quad (4)$$

Where:
$\rho$, the air density, in [kgm$^{-3}$].
$A$, the area swept by blades, in [m$^2$].
$V$, the wind average speed value constant, in [ms$^{-1}$].

## 3.3. Model of Output Power of Biogas Plant

Biogas is obtained by fermentation of organic matter. The degradation of organic substances takes places in several stages under the action of bacterial populations. In this paper, substrate from marine algae, animal manure and other agricultural wastes are mixed and exploited. Our biogas plant consists of two stacked biodigesters, in the biodigester placed on the upper floor, the fresh material arrives and takes place acetogenesis process. After a few days, the substrate passes into the second biodigester located at the bottom where the methanogenesis process takes place. Biomass system model based on mixed biomasses, the hourly energy generated by the biomass generator is determined using the equation expressed by [11, 17];

$$E_{BMG} = \frac{Biomass\ disponible\ \left(\frac{kg}{yr}\right)\times C_{VBMG}\times\eta_{BMG}\times\Delta t}{365\times\ 860\ \times h_{BGG}} \quad (5)$$

where,
$E_{BMG}$, output energy generated from biomass plant; $\eta_{BMG}$, as the system conversion efficiency,
$C_{VBMG}$ as biomass gasifier calorific value (4015 kcal/kg).

## 3.4. Model of Biogas Powered Generator Set

The energy produced by this biogas powered generator is calculated from the following equation [11, 17, 18]:

$$E_{BGG} = \frac{Biogaz\ disponible\ \left(\frac{m^3}{day}\right)\times CV_{BGG}\times\eta_{BGG}\times\Delta t}{860\ \times h_{BGG}} \quad (6)$$

Where,
$E_{BGG}$: the energy output of biogas generator,
$CV_{BGG}$: the biogas generator calorific value (4700 kcal/kg)
$\eta_{BGG}$: as system conversion efficiency.

## 3.5. Storage System

Solar and wind energy are classified as intermittent energy sources due to their variable nature, consequently, the employment of storage batteries is imperative to defer the voltage and current at the output of hybrid system. The storage capacity of batteries depends on the energy produced by the hybrid system as well as the load required.

The amount of energy stored at time t is represented as follows [11].

Energy supply exceeds energy demand: charging:

$$E_B(t) = E_B(t-1) + \left[E_G(t) - \left(\frac{C(t)}{\eta_{ond}}\right)\right] \times \eta_B \quad (7)$$

Energy supply is lower than energy demand: discharging

$$E_B(t) = E_B(t-1) + \left[\left(\frac{C(t)}{\eta_{ond}}\right) - E_G(t)\right] \quad (8)$$

Where,
$E_B(t)$ and $E_B(t-1)$: Battery charge quantities at times t and t-1
$\eta_{ond}$: Inverter efficiency,
C(t): energy demand,
$E_G(t)$: energy supply by PV/wind / Biogas generators
$\eta_B$: Battery efficiency.

At any time, the amount of charge in the batteries is subject to the following constraints:

$$E_{Batt\ min} \leq E_{Bat}(t) \leq E_{Batt\ max} \quad (9)$$

The maximum battery capacity is calculated as the nominal battery capacity, and the minimum capacity is determined by the depth of discharge (DOD).

$$E_{Batt\ min} = DOD.E_{Bat.N} \quad (10)$$

The maximum state of charge (SOC) value is 1, and the minimum is determined by the maximum depth of discharge.

$$SOC_{min} = 1 - DOD \quad (11)$$

## 3.6. Muscular Power in Agriculture

Since the origins of humanity, in agriculture, human and animal muscular forces have been necessary to produce the goods we consume, to transport the products of farmers. Muscular power is a source of renewable energy without pollution and promotes job creation [19].

### 3.6.1. Manual Human Power in Agriculture

Muscular power is the conversion of chemical energy to mechanical energy. The intercellular energy vector is ATP (Adenosine Triphosphate). L'ATP is the responsible of muscular contraction. The chemical conversion reaction of glucose to ATP is given below [20]:

$$6O_6 + C_6H_{12}O_6 \rightarrow 6CO_2 + 6H_2O + 38\ ATP \qquad (12)$$

The muscular efficiency is:

1) 78% thermal power (sudation),
2) 22% mechanical power.

Cultivator or manual worker involve a lot of physically demanding activity [21].

$$E_{jour} = E_{mb} + E_{alim} + E_{travail}\ \text{[kcal]} \qquad (13)$$

Where,

$E_{jour}$ Total energy expenditure, [kcal],
$E_{mb}$ Basic metabolic energy,
$E_{alim}$ Energy from nutrition,
$E_{travail}$ Energy available for work.

The average level of human power that can be maintained over a certain period of time is limited by the energy capacity of the organism.

This Figure 2 shows the long term human power capability [20].

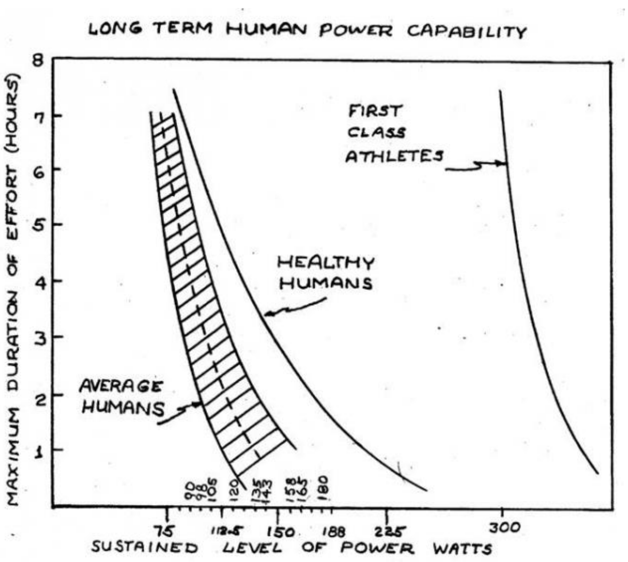


*Figure 1. Long term human power capability.*

As part of our study, we analyzed this Figure 1. We consider that a healthy worker can develop 100W during 8 hours.

Manpower supply refers to the availability and allocation of human resources or workforce that can be utilized to fulfill the requirements of hybrid energy supply system.

This includes employees, contractors, and temporary workers who possess different skills and expertise.

Muscular power is renewable natural resource that can assist not only in production, but also in land and transport with little external input [22].

As example, we demonstrated in Table 1 and Table 3, annual energy per unit for manual human tasks and animal traction tasks per unit are presented.

*Table 1. Manual human tasks.*

| Manual tasks | Annual energy per unit |
|---|---|
| Collection of biogas inputs | 10 kWh / T / manpower |
| Spreading organic fertilizers | 8 kWh / Ha / manpower |
| Manual farming labour | 16 kWh / Ha / manpower |
| Cleaning tasks | 3 kWh / manpower |
| Others | 3 kWh / manpower |

### 3.6.2. Animal Domestic Power in Agriculture

Animal traction denotes the use of domesticated animals by man for transportation and agricultural work [23]. Animal traction continues to increase in the developing countries. Animal power will continue to be important for food security, self-reliance and poverty alleviation. Animal power is renewable natural resource that can assist not only in production, but also in land and water. Animal power is a renewable energy source that can be sustained in rural areas with little external input. Working animals only consume food that is grown locally and produce natural fertilizer. They reproduce by themselves. Their use proved its work over millennia and it is difficult to conceive on an energy that is as easily accessible and as sustainable [23-25].

*Table 2. Power developed by animal domestic power [24].*

| Animal traction | Muscular power |
|---|---|
| Donkey | 150 - 250 W |
| Beef | 300 - 600 W |
| Horse | 400 - 800 W |

In Madagascar, farmers predominantly opt to engage in agricultural activities with domesticated beefs.

*Table 3. Animal traction tasks.*

| Animal traction tasks | Annual energy per unit |
|---|---|
| Transport of biogas inputs | 13 kWh / T / beef |
| Farming labour | 20 kWh / Ha / beef |
| Transport by cart | 20 kWh / km / beef |
| Others | 5 kWh / beef |

The design problem thus becomes an optimization problem. To continue our work, it is necessary to determine the optimal size of the HRESS. The method under discussion involves the optimization of an annual cost function, subject to a set of constraints, using a linear programming algorithm. In order to evaluate the quantity of energy delivered by different resources.

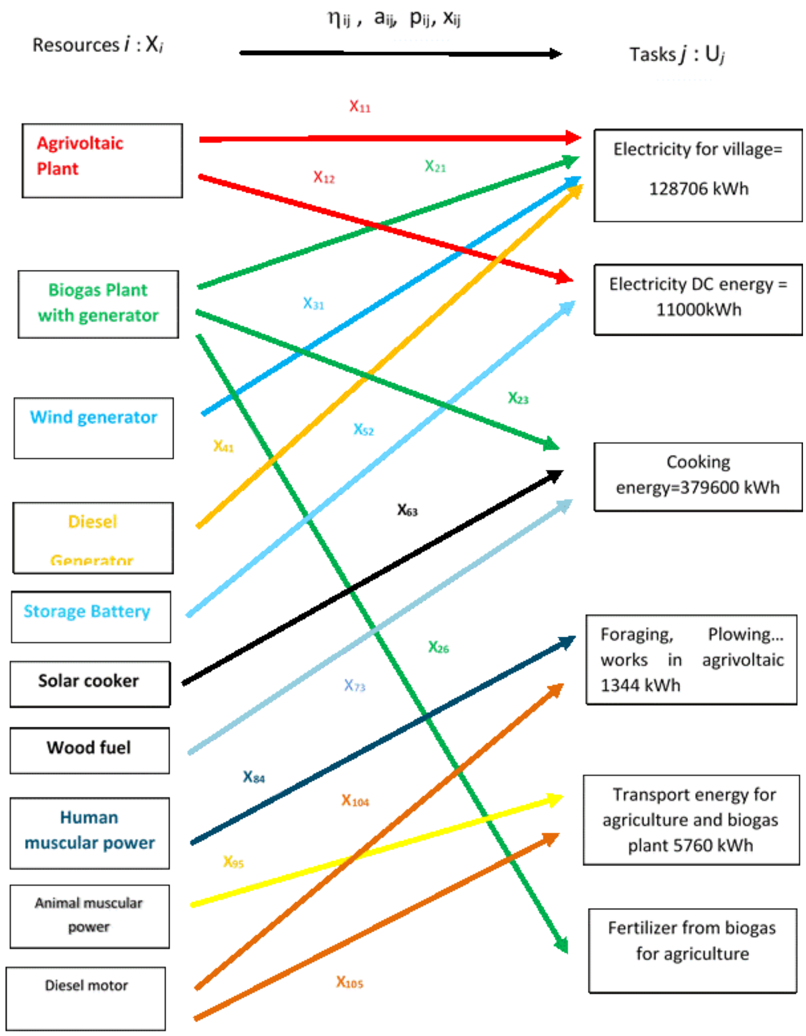


*Figure 2. Schematic for mathematical modeling of hybrid renewable energy system in remote rural village.*

## 4. Methodology for the Optimization of HRESS for Remote Rural Villages

### 4.1. State of Art

In rural area, design of stand-alone hybrid solar, wind and biogas plant have received the attention of researchers. A few hybrid solar, wind and biogas plants are operating around the world. In rural area, Ramakumar, A. et al. [7] employ linear programing as a tool to optimize stand-alone hybrid energy sources including biogas, solar, wind and water head plants. In this work, Ajasse, A., Meunier, S., Reinbold, V., Bureau, A., Rakotoniaina, S., H. and Labouré, E [26] integrate diesel generator to reduce the required photovoltaic and battery sizes. Modeling and linear optimization framework is used to optimize the sizing of microgrid componets. The approach is applied to a rural village of Antanamalaza in Madagascar. Kusakana, K., Vermaak, H., et al. [27] propose a linear programming approach to minimize investment costs while accounting for resource availability and demand. Simulations are performed using MATLAB, demonstrating the reliability and speed of this method. In this context, Bouharchouche et al. [28] introduce the Loss of Power Supply Probability (LPSP) as a key performance indicator, enabling optimization of the reliability of hybrid systems. Dhaker Abbes [29] explores techniques such as genetic algorithms and Sequential Quadratic Programming (SQP), which have proven effective in reducing both economic costs and environmental impacts.

Indoniavo, I. [30] employed a genetic algorithm to optimize the power distribution among the different energy sources, the load demand, and the storage components. The results were compared with those obtained using HOMER, revealing differences due to variations in economic and energy modeling. The sizing was conducted by integrating the management loop. An optimal configuration was identified, minimizing the Net Present Cost (NPC) while maintaining an LPSP below 5%.

Sahoo S. K. et al [31], Pamucar D. et al [32], Kamari M. L et al [33] applied Multi-Criteria Decision Making (MCDM) to build energy systems and optimize energy consumption, minimize costs, and reduce environmental impacts. Those literature reviews highlight the importance of combining mathematical methods, simulations, and resource management to optimize hybrid energy systems in varied and often challenging environments.

The objective of this work is to optimize the HRESS. This is a complex undertaken, given the constraints on renewable and muscular resources availability, as well as loads demands.

In order to facilitate comprehension of a given system, we resort to the utilization of simplified descriptions. The mathematical model of HRESS is presented in a linear form. The approach was applied to a rural village in Lavanono, located in the south of Madagascar.

## 4.2. HRESS Model in a Linear Form

### 4.2.1. The Model of Sources

The forms renewable source of energy are marked by the index “i”

The i-th source is used to completely or partially satisfy the users of the j-th form of energy or of the products obtained. The forms of energy and products obtained at the output are marked by the index “j” [7].

Evaluation of the parameter $X_i$ of renewable energy resources type «i ».

$$X_i = \sum_{j=1}^{k} x_{ij}, \text{ for the tasks j=1,2,…,k} \tag{14}$$

Where:

$x_{ij}$: the portion of parameter $X_i$ used to satisfy completely or in part the task **j**th form of energy or the products obtained.

Annual sum of energy $E_i$ obtained by ith resource

$$E_i = R_i X_i \text{ et } E_{ij} = R_i X_{ij}, \tag{15}$$

Where,

$E_{ij}$: part of $E_i$, which is used to have the jth form of energy or products obtained.

$R_i$: energy equivalents of the various resources «i ».

### 4.2.2. Formulation of Constraints

Formulation of constraints, considering the following conditions:

1) Energy balance between the i th source and the j th form of energy or products for users:

$$U_j = \sum_{i=1}^{n} R_i \eta_{ij} x_{ij}, \text{ [kWh]} \tag{16}$$

$i \rightarrow 1,...,n$

Where $\eta_{ij} = \frac{U_{ij}}{E_{ij}}$: efficiency of transmission of energy from source "i " to users " j " form of energy.

2) Power constraints:

$P_i \leq P_{ai}$,

where $P_i$: Maximum useful power obtained from i th source, Pai: rated power,

$$P_{ai} = \frac{E_i}{8760 f_i}, \tag{17}$$

Either

$$\left(\frac{1}{f_i}\sum_{j=1}^{k} x_{ij} - \frac{1}{d_i}\sum_{j=1}^{k}\frac{x_{ij}}{k_{ij}}\right) \geq 0 \text{ for i = 1,..,n} \tag{18}$$

fi; effective load factor of the plant,
di; diversity factor.

$$k_{ij} = \frac{U_j}{8760 P_{0j}} \tag{19}$$

3) All the $x_{ij}$ values must be positive,

$x_{ij} \geq 0$ for i = 1,2,…,n

J = 1,2,…, k

If, aij is the cost in dollars per kWh for the " i - j " combination; [USD/kWh],

$$a_{ij} = \frac{T_{crij} P_{ij}}{8760 k_{ij}} \tag{20}$$

For the solar radiation, the energy equivalent $R_p$ is the annual DC electrical energy per square meter from the APV array is:

$$R_p = \eta_p \sum_{n=1}^{8760} y_\alpha \text{ [kWh / m2 per year]} \tag{21}$$

The energy equivalent $R_w$ of the wind is the annual rotating mechanical shaft energy output from of wind turbines in kWh per square meter of swept area.

$$R_w = \eta_w \sum_{n=1}^{8760} V_\alpha^3 \quad [\text{kWh / m}^2 \text{ per year}] \tag{22}$$

In the case of muscular power, the energy equivalent of employees $R_e$.

The cost of each combination " i - j " is

$$C_{ij} = R_i a_{ij} x_{ij} \tag{23}$$

The total annual cost of this HRESS is given in the form of a linear programming problem:

$$C = \sum_{i=1}^{n} R_i \left\{\sum_{j=1}^{k} a_{ij} x_{ij}\right\} \rightarrow min \tag{24}$$

The mathematical model of HRESS is presented in a linear form. We should minimize the total annual cost. This is a complex undertaking, given the constraints on the availability of renewable and muscular resources, as well as load demands. As part of this study, we will verify the results obtained by the simplex method using the genetic algorithm.

## 4.3. Application of Genetic Algorithm and Multi-Criteria Decision-Making in Linear Model of HRESS

### 4.3.1. Functioning Within a Genetic Algorithm

A genetic algorithm (GA) is based on the idea of Darwinian evolution [33].

1) Initialization: Creation of a population of individuals (candidate solutions).
2) Evaluation: Fitness calculation (Quality of each solution).
3) Selection: Choosing the best individuals to reproduce.
4) Crossover: Combining two individuals to create new offspring.
5) Mutation: Random modification to introduce diversity.
6) Replacement: Updating the population with the new individuals.
7) Iteration: Repeating the cycle until a stopping criterion is reached (number of generations or target fitness).

DEAP (Distributed Evolutionary Algorithms in Python) is a powerful Python library that makes it easy to create and experiment with evolutionary algorithms, including genetic algorithms. It provides ready-to-use tools for selecting, crossing, mutating, and evaluating individuals in a population.

PyGAD is an open-source Python library dedicated to genetic algorithms and optimization. In the field of optimization, Pygad is a Python library specializing in algorithms. The main applications of Pygad include energy optimization.

### 4.3.2. Multi-Criteria Decision-Making for the Model of HRESS

MCDM method is employed in the field of energy engineering. The selection of the most appropriate renewable energy system depends on several factors. The criteria used in this study were divided into three main parts, including economic, environmental, and job creation [31-33].

$$Z = \propto \sum i(C_i\, x_i) + \beta \sum i(E_i\, x_i) - \gamma \sum i(R_i\, x_i) \tag{25}$$

Where,

*Ci:* unit cost (CAPEX/OPEX) of source i,

$E_i$: $CO_2$ emission factor ($tCO_2$/kWh) of source i

$R_i$: renewability coefficient (0 = no renewable, 1 = renewable) of source i

$x_i$: decision variable (energy produced, parameters of plant power)

$\alpha, \beta, \gamma$: weighting coefficients.

## 5. Case Study for Remote Rural Village Lavanono

Lavanono is a fishing village located in the extreme southwest of Madagascar, about 20 km from Cap Sainte Marie in the district of Beloha, Androy region [30].


***Figure 3.*** *Location of the village of Lavanono.*

## 5.1. Natural Resource Deposits at the Site

Due to its unique ecosystem and the presence of endemic species, the village of Lavanono has great tourism potential. However, the lack of access to energy and other infrastructure significantly hinders its development in this area. Fishing is the main activity of the inhabitants of Lavanono, with a variety of resources such as fish, crabs, lobsters, and other seafood [30].

The NASA POWER project's Data Access Viewer (DAV) is an interactive web-mapping application providing access to NASA solar and meteorological data. As illustrated in Figure 4, the solar potential in the vicinity of the village of Lavanono [34] is considered in the design of the agrivoltaic power plant.

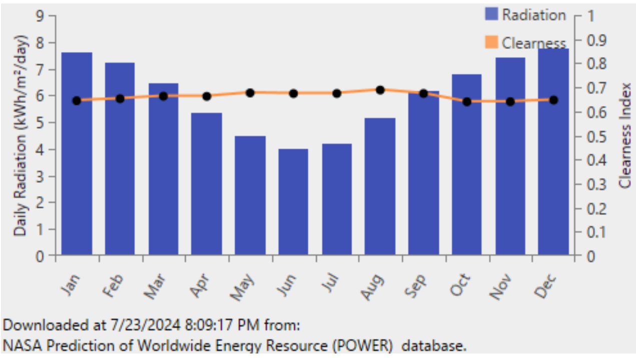


***Figure 4**. Solar radiation of village Lavanono.*

### 5.1.1. Study Frameworks

This study aims to assess the design of the HRESS, using the village of Lavanono as a case study. The village currently has around 1,200 inhabitants, and the number of households with electricity is estimated at 65. Annual energy consumption is estimated at 128,706 kWh/year [30]. Based on our estimate, the daily electricity load profile curve is shown in Figure 5 below:

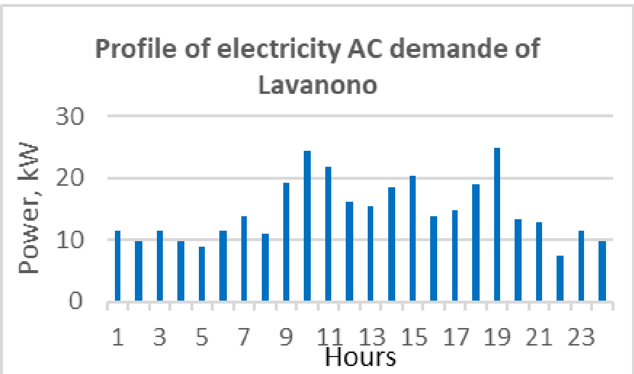


***Figure 5**. Daily profile of energy consummation.*

As part of this study, particular attention was paid to the interaction between solar, muscular, and agricultural energy sources. Figures 7 and 8 show the annual muscle energy sources, taking into account local socio-economic and climatic realities.

Agricultural seasons [30]:

1) Rainy season: October to April: peak growing season rice, cassava, maize…)
2) Dry season: May to September: reduced activity, maintenance, late harvest.

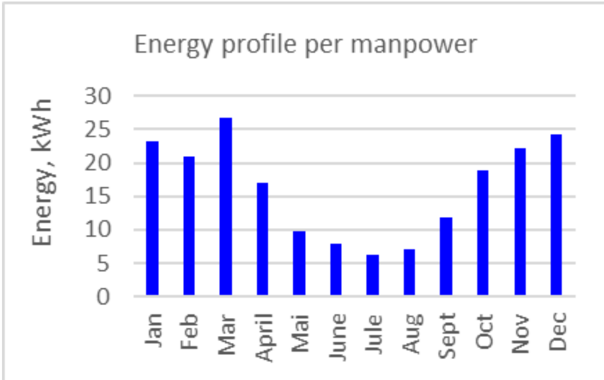


***Figure 6**. Energy offered per manpower upon climatic conditions.*

The manual annual manpower tasks are as follows:

1) Collection of biogas inputs
2) Spreading organic fertilizers
3) Manual farming labor under agrivoltaic plant (rice, maize, potato, cassava)

Figure 6 is obtained by taking into account the climatic conditions of the region. In the present calculation, it is assumed that a cultivator supplies 100W [20] of power for 8 hours per day, and works for 240 days per year. This gives an estimated annual consumption of 192 kWh.

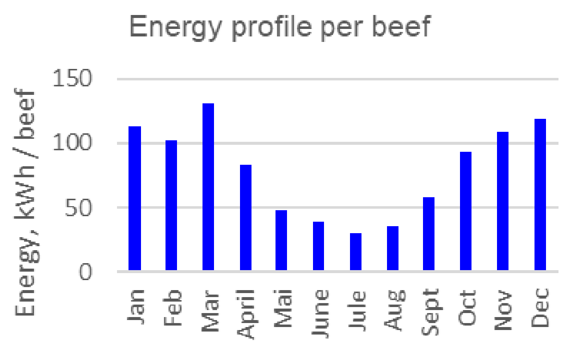


***Figure 7**. Energy demand per beef upon climatic conditions.*

The annual animal tasks are as follows:

1) Collection and transport biogas inputs (biomass mixed)
2) Farming labor
3) Transportation

This Figure 8 shows the energy profile provided by beef as a function of regional climate. Less work is required during the dry season. In the present estimation, it is assumed that a beef supplies 500W [24] of power 8 hours per day, and works for 240 days per year. This gives an estimated annual consumption of 960 kWh.

### 5.1.2. Design off HRESS

According to Figure 3, our HRESS integrates several renewable energy sources: solar, wind, algae biomass, diesel generator, lithium battery, human muscle power, and animal muscle power.

Apart from this, the indeterminacy of the initial information complicates the resolution of the model obtained. The objective function takes into account the following parameters: energy equivalent Ri, specific costs $a_{ij}$, utilization efficiency of the "i - j" combination. These parameters are scattered and depend on climatic conditions, market prices for materials, scientific discoveries and the possibility of local mass production of energy equipment from renewable energy sources.

For this work, the resolution of this linear programming model is based on the simplex method and confirmed by genetic algorithm.

The technical and economic parameters of the various "i-j" combinations mentioned in Figure 2 are listed in Table 4 below [7, 12, 26, 30, 33-39].

***Table 4.*** *Technical and economic parameters of combination "i-j".*

| Combination "i-j" | Capital cost values per year, pij | Cost per kWh aij | Energy Equivalents, Ri | Transmission efficiency, nij | Load factor, kij |
|---|---|---|---|---|---|
| Agri-PV Electricity AC: $x_{11}$ | 1500 $ / kW | 0.049 $ / kWh | 541.6 kWh/m²/yr | 0.85 | 0.59 |
| Agri-V - Electricity DC: $x_{12}$ | 1300 $ / kW | 0.062 $ / kWh | 541.6 kWh/m²/yr | 0.6 | 0.40 |
| Biogas - Electricity AC: $x_{21}$ | 2000 $ / kW | 0.065 $ / kWh | 2.33 kWh/m³ | 0.35 | 0.59 |
| Biogas - Cooking: $x_{23}$ | 500 $ / kW | 0.016 $ / kWh | 4.07kWh/m³ | 0.40 | 0.60 |
| Biogas - Fertilizer $x_{26}$ | 200 $ / kW | 0.013 $ / kWh | 400 m3 / ton | 0.75 | 0.85 |
| Wind - Electricity AC $x_{31}$ | 2100 $ / kW | 0.068 $ / kWh | 230 kWh/m²/yr | 0.85 | 0.59 |
| Diesel - Electricity AC $x_{41}$ | 800 $ / kW | 0.052 $ / kWh | 3 kWh / litre | 0.4 | 0.59 |
| Battery - Electricity DC: $x_{52}$ | 500 $ / kW | 0.024 $ / kWh | 0.90 kWh / kWh | 0.85 | 0.40 |
| Solar - Cooking: $x_{63}$ | 40 $ / kW | 0.001 $ / kWh | 434.35 kWh /unit/yr | 0.35 | 0.60 |
| Fuelwood - Cooking: $x_{73}$ | 50 $ / kW | 0.005 $ / kWh | 4 kWh / kg | 0.13 | 0.60 |
| Human muscular- traction: $x_{84}$ | 1000 $ / kW | 0.087 $ / kWh | 192kWh/Man/yr | 0.60 | 0.22 |
| Animal muscular - transport: $x_{95}$ | 2500 $ / kW | 0.218 $ / kWh | 960kWh/beef/yr | 0.60 | 0.22 |
| Diesel motor - Traction: $x_{104}$ | 4000 $ / kW | 0.335 $ / kWh | 5000kWh/motor/yr | 0.40 | 0.23 |
| Diesel tractor - Transport: $x_{105}$ | 4000 $ / kW | 0.335 $ / kWh | 5000kWh/tractor/yr | 0.60 | 0.23 |

***Table 5.*** *Conversion efficiency from source "i" to load "j" [7].*

| Energy source | Diversity factor $d_i$ | Effective load factor plant $f_i$ | Annual operating hour |
|---|---|---|---|
| Agri-PV plant AC | 1.2 | 0.22 | 4200 h |
| Agri-PV plant DC | 1.4 | 0.30 | 4200 h |
| Biogas plant AC | 1 | 0.20 | 4200 h |
| Biogas cooking | 1 | 0.22 | 3500 h |
| Fertilizer from biogas | 1 | 0.21 | 1200 h |
| Wind generator | 1 | 0.21 | 4200 h |
| Diesel generator | 1 | 0.21 | 3500 h |

| Energy source | Diversity factor $d_i$ | Effective load factor plant $f_i$ | Annual operating hour |
|---|---|---|---|
| Battery storage | 1 | 0.21 | 1200 h |
| Solar cooker | 1 | 0.21 | 1200 h |
| Wood fuel | 1 | 0.21 | 3500 h |
| Human power | 1 | 0.21 | 1200 h |
| Animal traction | 1 | 0.21 | 1200 h |
| Diesel motor | 1 | 0.21 | 400 h |
| Diesel tractor | 1.2 | 0.22 | 600h |

## 6. Results of Simulation

Following to the completion of the descent and data collection at the Lavanono village site, and in consideration of the information enumerated in the preceding subparagraphs, the objective function and constraint equations that characterize the optimization of HRESS can be established.

### 6.1. First Step: Simulation With no Upper Limit on the Variables $x_{ij}$

*Objective function* $Z = 26.3x_{11} + 33.7x_{12} + 0.151x_{21} + 0.065x_{23} + 5.4x_{26} + 16x_{31} + 0.155x_{41} + 0.024x_{52} + 0.5582x_{63} + 0.0255x_{73} + 16.746x_{84} + 209.325x_{95} + 1674.6x_{104} + 1674.6x_{105}$

*Under constraints:*

$460.40x11 + 0.81x21 + 195.46x31 + 1.20x41 = 128706$

$324.99x12 + 0.765x52 = 11000$

$1.63x23 + 153.3x63 + 0.52x73 = 379600$

$115.2x84 + 2000 x104 = 1344$

$576x95 + 3000 x105 = 5760$

$300x26 = 37382$

$3.13x11 + 1.55x12 \geq 0$

$3.31x21 - 1x23 + 3.59x26 \geq 0$

$3.07x31 \geq 0$

$3.07x41 \geq 0$

$2.26x52 \geq 0$

$3.10x63 \geq 0$

$3.10x73 \geq 0$

$0.20x84 \geq 0$

$0.20x95 \geq 0$

$0.38x104 \geq 0$

$0.90x105 \geq 0$

x11, x12, x21, x23, x26, x31, x41, x52, x63, x73, x84, x95, x104, x105 $\geq 0$.

The linear programming simplex method and algorithm, implemented in Python, were solved using the formulation from DEAP and PyGAD.

To minimize a linear sum of total cost Z object to a linear constraint, the optimal solution is to allocate all the necessary energy to the variable that minimizes the ratio of the objective coefficient to the constraint coefficient. Consequently, the other coupled constraint variables are zero.

In the first scenario, the various sources of alternating current (AC) electricity generation and the various sources of domestic cooking energy are not limited by the constraints of the model. As part of our methodological approach, we use GA, a heuristic approach aimed at retrieving the values calculated by the simplex method. The GA solution is compared to the simplex solution. The necessary operators: population size 200; generations 800; crossover rate 0.85; mutation rate 0.15; blend crossover BLX-$\alpha$ = 0.5; tournament k = 3.

The resulting values are shown in Table 6 below.

***Table 6.*** *Design and energy values results of HRESS.*

| Combination "i-j" | Solution by simplex method | Solution by Algorithm genetic | Energy per year | Design HRESS |
|---|---|---|---|---|
| Agr-PV-AC: $x_{11}$ | 0 [$m^2$] | 0 [$m^2$] | 0 [kWh] | 0 [kW] |
| Agri-PV-DC: x12 | 0 [m2] | 0 [m2] | 0 [kWh] | 0 [kW] |
| Biogas - Electricity AC: x21 | 0 [m3] | 0 [m3] | 0 [kWh] | 0 [kW] |
| Biogas - Cooking: x23 | 0 [m3] | 0 [m3] | 0 [kWh] | 0 [kW] |
| Wind AC: x31 | 0 [m2] | 0 [m2] | 0 [kWh] | 0 [kW] |

| Combination “i-j” | Solution by simplex method | Solution by Algorithm genetic | Energy per year | Design HRESS |
|---|---|---|---|---|
| Diesel generator AC x41 | 107 255 [L/year] | 107 255 [L/year] | 128 551 [kWh] | 30 [kW] |
| Battery: x52 | 14379 [kWh/year] | 14379 [kWh] | 11 000 [kWh] | 5 [kW] |
| Solar Cooking: x63 | 0 [unit/year] | 0 [unit/year] | 0 [kWh] | 0 [kW] |
| Fuel wood cooking: x73 | 730 000 [kg/year] | 730 000 [kg/year] | 379 600 [kWh] | 108 [kW] |
| Manpower: x84 | 12 [Manpower] | 12 [Manpower] | 1382.4 [kWh] | 2 [kW] |
| Beefs for traction: x95 | 10 [beef] | 10 [beef] | 5760 [kWh] | 5 [kW] |
| Diesel motor labour: x104 | 0 [unit] | 0 [unit] | 0 [kWh] | 0 [kW] |
| Diesel tractor: x105 | 0 [unit] | 0 [unit] | 0 [kWh] | 0 [kW] |
| Fertilizer from biogas x26 | 0 [ton /year] | 0 [ton/year] | 0 [kWh] | 0 [kW] |
| TOTAL ENERGY | | | 532 274 [kWh] | |
| TOTAL COST | 37 489 USD | 38 052 USD | | |

In this first case study, our objective is to minimize the total cost of HRESS. The results were obtained using the simplex method in Table 6. Successive pivoting leads to a solution where these variables take on values compatible with their constraints we did not set limits on all the sources for HRESS energy production. Electricity production is entirely provided by the diesel generator who consumes $x_{41}$= 107,255 liters of diesel annually, which corresponds to a power $X_4$ = 30 kW. The cooking energy of rural households is entirely supplied by fuel wood of $x_{73}$ =730,000 kg per year, i.e., power $X_7$ = 108 kW for the entire population of the village of Lavanono of Madagascar. For the operation of the HRESS, two equalities of constraint directly fix the variables $x_{84}$ = 12 manpower for agricultural and livestock work and $x_{95}$ =10 beef to pull 5 carts for transporting agricultural products. The coefficients of the motorized work variables $x_{104}$ and $x_{105}$ are very high (1674.6), so the simplex method minimizes them to zero. Minimizing the total cost Z results in the variables x11, x12, x21, x23, x26, x31, and x63 equaling zero, yielding Z = 37,489 USD. These results were in Table 6 also found using a genetic algorithm. The simulation ran with the GA parameters defined above. The minimum cost obtained is Z = 38,052 USD. The minimization results obtained via the GA converge toward a solution very close to that of the simplex method.

The next stage of our study involves using of multi-objective function. The objective is to minimize the total cost, $CO_2$ emissions and increase the amount of renewable energy sources integrated into the HRESS system.

## 6.2. Second Step: Optimization with Multi-criteria Objective Function

Instead of minimizing only Z (cost), multiple objectives are introduced. The weighting method is used [32, 33]. The principle involves combining them into a single function with coefficients. Simple to implement and compatible with linear programming. This is an extension of the simplex method to multiple objectives.

$$Z = \propto \sum i(C_i\, x_i) + \beta \sum i(E_i\, x_i) - \gamma \sum i(R_i\, x_i) \tag{23}$$

Where,

*Ci:* unit cost of source i,

$E_i$: $CO_2$ emission factor ($tCO_2$/kWh) of source i

$R_i$: renewability coefficient (0 = no renewable, 1 = renewable) of source i

$x_i$: decision variable (energy produced, parameters of plant power)

$\alpha, \beta, \gamma$: weighting coefficients.

### 6.2.1. Weighting Coefficients

The weighting coefficients $\alpha$, $\beta$, *and* $\gamma$ allow assigning weights to each criterion according to priority.

Weighting coefficient $\alpha$ for cost per unit, weighting coefficient $\beta$: for $CO_2$ emission, weighting coefficient $\gamma$: for renewable energy sources. In this case, for our HRESS, equation (23) becomes:

***Table 7.*** *Multi-criteria of source [31-33].*

| Source | Unit cost | $CO_2$ emission [$tCO_2$/kWh] | Renewability (1 or 0) |
|---|---|---|---|
| Agrivoltaic plant $x_{11}$ | 26.3 | 0.02 | 1 |
| Biogas plant $x_{21}$ | 0.151 | 0.05 | 1 |
| Fertilizer bio $x_{26}$ | 5.4 | 0.10 | 1 |
| Wind park $x_{31}$ | 16 | 0.01 | 1 |
| Diesel generator $x_{41}$ | 0.155 | 0.85 | 0 |
| Battery lithium $x_{52}$ | 0.024 | 0.01 | 0 |
| Solar cooking $x_{63}$ | 0.558 | 0.02 | 1 |
| Wood fuel $x_{73}$ | 0.025 | 0.45 | 1 |
| Human power $x_{84}$ | 16.74 | 0.01 | 1 |
| Animal power $x_{95}$ | 209.3 | 0.02 | 1 |
| Motor diesel $x_{104}$ | 1674.6 | 0.85 | 0 |
| Tractor diesel $x_{105}$ | 1674.6 | 0.85 | 0 |

Based on Table 7, the equation of the multi-criteria objective function for the HRESS in the village of Lavanono becomes as follows:

### 6.2.2. Criteria for HRESS Energy Sources

Our model is becoming a multi-criteria decision-making tool. In this section, we aim to address three objectives:

1) Minimizing costs (CAPEX/OPEX),
2) Minimizing $CO_2$ emission,
3) Maximizing renewable sources.

As an expected result, we will generate the three-dimensional Pareto front.

In this second step, the integration of a significantly greater quantity of renewable energy sources into the HRESS will be achieved by additional optimization constraints; the distribution of coupled variables is determined by means of a weighting index based on the percentage.

$$Z=\alpha\cdot(26.3X_{11}+0.151X_{21}+16X_{31}+0.155X_{41}+5.4X_{26}+0.024X_{52}+0.558X_{63}+0.025X_{73}+16.74X_{84}+209.325X_{95}+1674.6X_{104}+1674.6X_{105}) + \beta\cdot(0.02X_{11}+X_{21}+X_{31}+0.85X_{41}+0.10X_{26}+0.01X_{52}+0.02X_{63}+0.45X_{73}+0.01X_{84}+0.02X_{95}+0.85X_{104}+0.85X_{105}) - \gamma\cdot(X_{11}+X_{21}+X_{31}+X_{26}+X_{63}+X_{73}+X_{84}+X_{95}).$$

***Table 8.*** *Front Pareto of HRESS.*

| Scenario | Method | Cost Z [USD] | $CO_2$ emission [$tCO_2$/kWh] | Share of renewable | Dominant sources |
|---|---|---|---|---|---|
| A: Minimum cost | Simplex | 65800 | 420 | 25% | Fuelwood + Diesel |
| B: Balance | Simplex multi-criteria | 68200 | 260 | 65% | APV + Wind + Biogas |
| C: Intermediate compromise | Genetic algorithm (Pareto) | 70500 | 150 | 80% | APV + Wind + Biogas |
| D: Maximum durability | Genetic algorithm (Pareto) | 72000 | 80 | 92% | APV + Wind + Biogas + Muscular power |

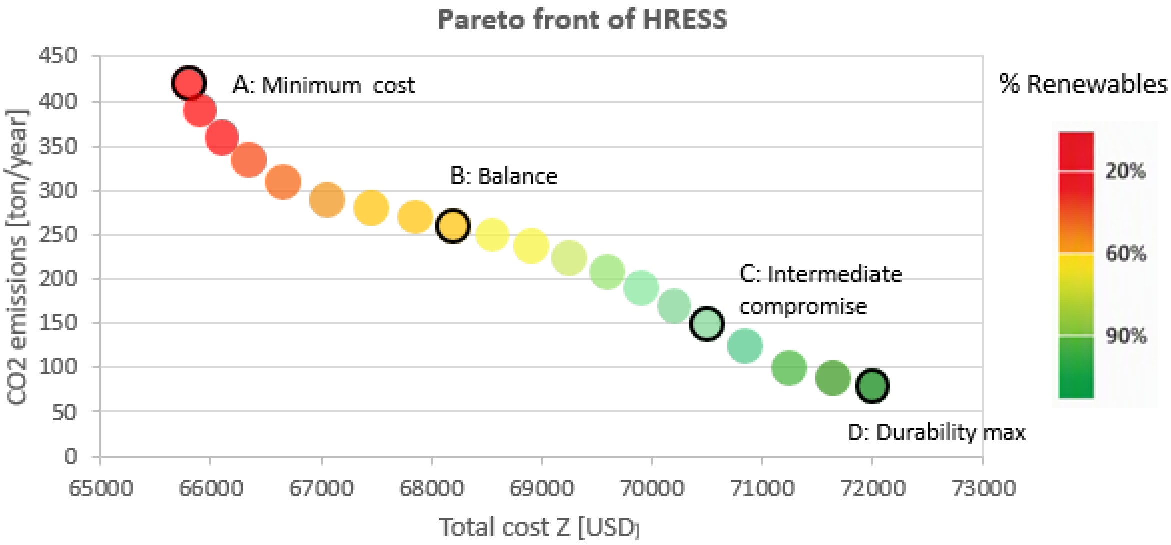


***Figure 8.*** *Three-dimensional Pareto front of HRESS.*

Scenario A: minimizes cost, but relies heavily on wood and fossil fuels. So, high $CO_2$ emissions.

Scenario B: balances cost and sustainability. So renewables-dominated, with reduced $CO_2$ emissions.

Scenario C: intermediate compromise proposed by GA. So, good operating point between cost and sustainability.

Scenario D: maximizes sustainability. So, nearly 100% renewable, but higher cost.

## 7. Conclusions

In this work, rural labor and animal traction by beef have been integrated as sources of energy in the Hybrid Renewable Energy System Supply. This article presents a method for designing a Hybrid Renewable Energy System Supply capable of utilizing several power plants such as an agrivoltaic array, biogas plant, wind generator and muscular energy for supplying the basic needs in the remote rural out of grid of developing countries.

The methodology employed in the design of this hybrid system is a combination of linear simplex method and the genetic algorithm. In the first step, the genetic algorithm solution is then compared to the simplex solution. The approach is based on minimizing an objective function of total annual cost with no upper limit on the variables $X_{ij}$.

In the second step, there is an extension of the simplex method to multiple objectives. The genetic algorithm is a heuristic approach that is used to optimize multi-criteria objective function that provides a three-dimensional Pareto front: a map of the tradeoffs between total cost, $CO_2$ emissions, and solar, wind, biogas and muscular power renewable energy sources.

This approach has been illustrated with the help of a numerical example for a typical village Lavanono in South of Madagascar. Obviously, the optimum values obtained for the various quantities very much depend on the values chosen for the parameters of muscular and other sources of renewable energies, which may vary widely depending on local conditions. Sustainability is not an absolute cost, but a choice that can be optimized according to local priorities: funding, environment and social acceptance.

In perspective, the use of evolutionary algorithms (NSGA-II, SPEA2) is computationally more intensive and requiring parameter tuning, yet highly effective for complex, non-linear problems and yield a range of trade-offs.

## Abbreviations

| | |
|---|---|
| HRESS | Hybride Renewable Energy Supply Systems |
| Agri-PV | Agriculture PhotoVoltaic |
| JIRAMA | JIro Sy RAno Malagasy (National Electricity and Water Company of Madagascar) |
| NPE | New Policies Energy |
| STC | Standard Test Conditioning |
| GA | Genetic Algorithm |
| BMG | BioMasse Generator |
| VBMG | Value of BioMasse Generator |
| BGG | BioGas Generator |
| DOD | Depth Of Discharge |
| SOC | State Of Charge |
| ATP | Adénosine TriPhosphate |
| DEAP | Distributed Evolutionary Algorithms in Python |
| PyGAD | Python Genetic Algorithm |
| LPSP | Loss of Power Supply Probability |
| GIZ | The German Society for International Cooperation |

## Author Contributions

**Solofo Hery Rakotoniaina:** Conceptualization, Methodology, Writing – review & editing
**Iderana Indoniavo:** Data curation
**Harlin Andriatsihoarana:** Supervision, Validation

## Conflicts of Interest

The authors declare no conflicts of interest.

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