International Journal of Engineering Inventions
e-ISSN: 2278-7461, p-ISSN: 2319-6491
Volume 14, Issue 2 [February. 2025] PP: 132-141

« Multi-objective approach on costs, Resilience, Social Inclusion, and Energy Transition using MOPSO applied to the Interconnected Network of Antananarivo, Madagascar »

Zandrison Richard RALAHIARIJAONA[1],
Electrical Engineering, ED STII, University of Antananarivo, Madagascar
Solofo Hery RAKOTONIAINA[2],
Electrical Engineering, ED STII, University of Antananarivo, Madagascar
Falimanana RANDIMBIDRAINIBE[3],
Mathematician and Physicist, ED STII, University of Antananarivo, Madagascar

[1] *PhD Student, Host Team Electrical Engineering,Doctoral School of Engineering Science and Technology and Innovation (ED STII), University of Antananarivo, Madagascar,*
[2] *Thesis co-Director, PhD of Electrical Engineering, Host Team Electrical Engineering,Doctoral School of Engineering Science and Technology and Innovation (ED STII), University of Antananarivo, Madagascar,*
[3]*Thesis director, PhD of Mathematics and Physics, Full professor, Host Team Cognitive Sciences,Doctoral School of Engineering Science and Technology and Innovation (ED STII), University of Antananarivo, Madagascar,*

ABSTRACT: *This paper presents a multi-objective approach based on the Multi-Objective Particle Swarm Optimization (MOPSO) algorithm to optimize the planning of the Antananarivo Interconnected Network (AIN), operated by Jiro and Rano Malagasy (JIRAMA). The aim of this work is to balance four key criteria: cost minimization, network resilience improvement, social inclusion promotion and energy transition acceleration. The study shows the performance of AIN with integrating real data from JIRAMA. The results demonstrate that the MOPSO approach significantly reduces operational costs while enhancing network reliability and renewable energy integration. Also, the social impact analysis highlights improved energy accessibility for vulnerable populations. These findings provide strategic insights for modernizing Madagascar's power grid. It can be used like some policy recommendations for a sustainable energy strategy that balances economic viability and social equity.*

Keywords: *resilience, transition, inclusion, energy, multi-objective, JIRAMA*

NOMENCLATURE

Symbol	Description	Unit
CA_k	Cost of access to energy	*Ariary*
C_{co2}	Cost of CO_2 emission produced by generator i	*Ariary*
$C_{Combustible}$	Cost per unit of energy for thermal power plants	*Ariary*
C_i	Cost of electricity production	*Ariary*
$C_{investment}$	Investment cost	*Ariary*
$P_{disponible}$	Power unit's available capacity	*Megawatts*
$P_{fossile}$	Proportion of energy production from fossil fuels.	*Megawatts*
P_i	Power from plant i	*Megawatts*
P_{max}	Maximum capacities of generator i	*Megawatts*
P_{min}	Minimum capacities of generator i	*Megawatts*
$P_{renouvelable}$	Power production of renewable energy	*Megawatts*
P_{total}	Total network capacity	*Megawatts*

Greek letter

Date of Submission: 14-02-2025 Date of acceptance: 28-02-2025

I. INTRODUCTION

Optimizing power generation is a crucial challenge in the global energy transition, particularly in the face of climate change, rising energy demand and the growing integration of renewable energies [1], [2]. With the rise of renewable energies such as solar, wind and biomass, optimizing power generation is essential to guarantee the reliability, safety and efficiency of distribution networks [2], [4]. However, this transition poses complex challengesin terms of cost management, system resilience and social inclusion [3], [6]. The variability of renewable energy sources, the need to reduce greenhouse gas emissions and promote universal access to energy call for innovative approaches [4]. Power systems need to be not only efficient, but also robust and inclusive, taking into account the social and economic specificities of the regions concerned [5], [9].

In this context, effective energy planning is essential to ensure a successful energy transition, while optimizing costs, resilience and social inclusion. Such planning must minimize energy production costs, while ensuring the integration of renewable energies, reducing CO_2 emissions, and supporting equitable access to electricity, particularly in the most disadvantaged regions [6]. Integrated energy system planning goes beyond optimizing energy production costs. It takes into account the complex interactions between different energy sectors such as electricity, thermal, renewables and energy storage needs also, demand management as well as social and environmental impacts [7]. The integration of resilience criteria is also essential in such planning. Energy systems must be able to cope with disruptions, whether natural like a climatic disasters or man-made like a breakdowns or attacks on infrastructure. The resilience of an energy network is therefore a key factor in its long-term performance [8], [13]. Then, social inclusion must be a priority in energy planning, in particular by ensuring that the most vulnerable populations have access to affordable and sustainable energy services. Social inclusion refers to reducing inequalities in access toelectricity [9], [14]. And finally, energy transition refers to increase a renewable energy sources [10], [15].

The central problem of this study lies in the simultaneous optimization of several objectives related to electric power generation, including cost reduction, improved energy system resilience, social inclusion and the promotion of energy transition.

The objectives of this study are as follows: first, propose an integrated energy system planning model that optimizes several criteria simultaneously such as costs, resilience, social inclusion and energy transition. Second, assess the impact of these optimization solutions. And third, compare the results obtained using a traditional planning approach and those using an optimization algorithm MOPSO.

The main contributions of this article are as follows: first, development of a multi-objective model for power generation planning that includes economic, social and environmental dimensions, second, analysis of the impact of multi-objective optimization on energy system resilience, production costs, social inclusion and energy transition in Madagascar and third, evaluation of the proposed solutions in comparison with planning without optimization algorithms to highlight the advantages and limitations of using algorithmic approaches to solve these complex problems.

II. EXPERIMENTAL SETUP

The problem of optimizing power generation in this study is based on integrated energy system planning. The aim is to determine the best possible configuration for power generation and distribution within the constraints of the system, while seeking to optimize several criteria such as cost, resilience, social inclusion and energy transition. The problem can be formulated as a multi-objective problem in which several criteria have to be optimized simultaneously: minimize energy production costs, maximize the resilience of the energy network, optimize social inclusion, in particular by reducing inequalities in access to energy and finally, support the energy transition by integrating renewable energy sources.

II.1 Mathematical formulation and objective functions with constraints

The mathematical formulation is based on a multi-objective programming model. The objective functions are based on the following criteria: first, the production costs, the total cost of power generation can be expressed as the sum of the costs of the different power generation technologies, taking into account operating and maintenance costs, as well as capital costs and fuel costs for thermal power plants [2], [12]. The cost function can be formulated as follows:

$$f_{cout} = \sum_{i} [C_i(P_i) + C_{combustible} \times P_{fossible}] \tag{1}$$

where $[C_i(P_i)$ is the cost of electricity production for the plant i as a function of production, $C_{combustible}$ is the cost per unit of energy for thermal power plants and $P_{fossible}$ is the proportion of energy production from fossil fuels. Secondly, network resilience is linked to its ability to withstand disruptions and recover quickly. This function can be formulated as maximizing the network's redundancy capacity[10], [13]. This resilience function can be formulated as follows:

$$f_{resilience} = \sum_{j} (1 - \frac{P_{disponible}(j)}{P_{total}}) \qquad (2)$$

where $P_{disponible}$ is the unit's available capacity andP_{total} is the total network capacity. Thirdly, social inclusion can be measured by reducing the gap in access to energy between different populations[6], [14], [21]. This function aims to minimize access costs for rural or poor areas:

$$f_{inclusion} = \sum_{k} (CA_k) \qquad (3)$$

where CA_k is the cost of access to energy for the population which can depend on distance from a grid, energy prices and inclusion policies. And finally, integrating renewable energies into energy production reduces the carbon footprint and supports the energy transition [15], [23]. This function can be formulated as maximizing the share of renewable production in the total energy mix:

$$f_{transition} = \sum_{r} (1 - \frac{P_{renouvelable}(r)}{P_{total}}) \qquad (4)$$

where $P_{renouvelable}(r)$ is the production of renewable energy from the source and P_{total} is the system's total output.

The energy system constraints involved in optimization are diverse and must be taken into account to guarantee the feasibility of the proposed solutions. These constrains can be grouped into several categories: technical constraints, ie, generator capacity and balance between demand and production. The capacity of each generator must be less than its maximum capacity and above its minimum capacity [1], [3].

$$P_{min}(i) \le P_i \le P_{max}(i) \qquad (5)$$

Where $P_{min}(i)$ and $P_{max}(i)$ represent the minimum and maximum capacities of generator i, respectively.

And total energy production must be equal to demand, adjusted for transmission losses [2], [12].

$$\sum_{i} P_i + \sum_{r} P_{renouvelable}(r) = P_{demand} \times (1 - losses) \qquad (6)$$

Where P_{demand} is the total energy demand and losses is the transmission loss factor.

The total cost of infrastructure investments must be less than an overall budget[5], [19]. and the operating and maintenance costs of different technologies must also respect economic limits [2], [16].

$$\sum_{i} C_{investment}(i) + C_{investment}(renouvelable) \le budget \qquad (7)$$

Where $C_{investment}(i)$ is the investment cost for generator i and $C_{investment}(renouvelable)$ is the cost of renewable energy infrastructure.

A certain percentage of the population must have access to electricity at affordable prices [6], [14], [21]

and finally, CO2 emissions from thermal power plants must not exceed a maximum limit [9], [23] and the proportion of energy from renewable sources must meet a minimum threshold to support the energy transition [4], [23].

$$\sum_{k} CA_k \le affordability\ threshold \qquad (8)$$

Where CA_k represents the cost of access for population k.

$$\sum_{i} C_{co2}(i) \le CO_2\text{limit} \qquad (9)$$

Where $C_{co2}(i)$ is the CO_2 emission produced by generator i typically based on its fuel type and energy production.

$$\frac{\sum_r P_{renouvelable}(r)}{P_{total}} \ge minimum\ threshold \qquad (10)$$

II.2 Presentation of algorithm MOPSO

To solve this multi-objective problem, the Multi-Objective Particle Swarm Optimization is used. This algorithm uses particles to explore the solution space and find an approximation to the Pareto frontier.We divide by 2 steps. The diagram on figure 1 shows MOPSO optimization diagram.

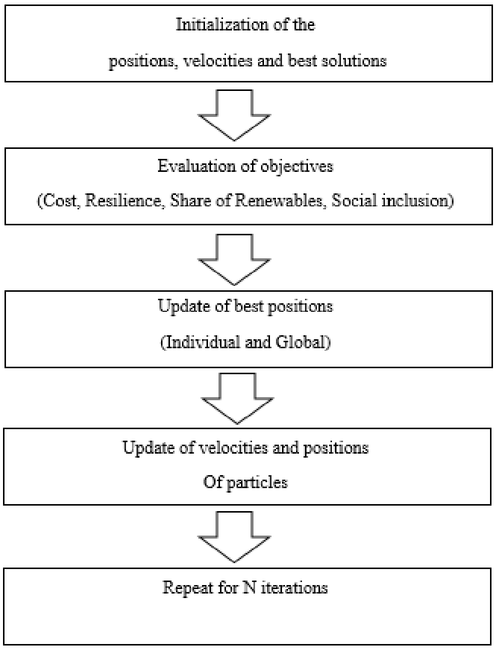

Figure 1 MOPSO Optimization diagram

Once the optimization is complete, the algorithm generates several graphs to visualize the evolution of various variables; such as demand, production, production cost, resilience, share of renewable energy and social inclusion. The diagram on figure 2 shows the results visualization diagram.

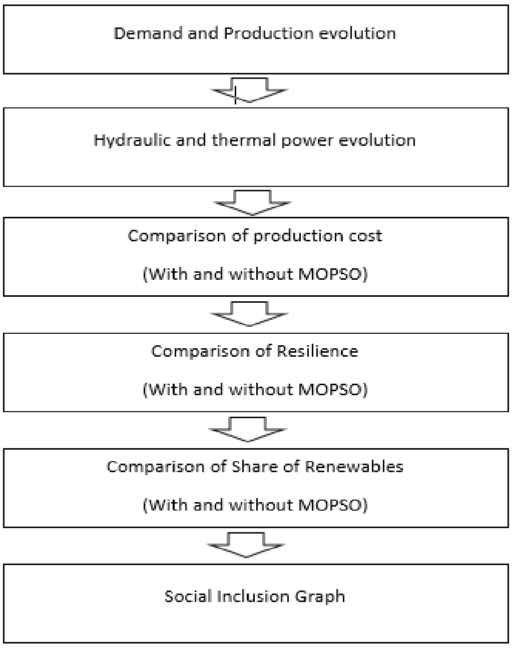

Figure 2 Results visualization diagram

These diagrams represent the main steps of the algorithm, distinguishing between the optimization part (MOPSO) and the visualization of the results obtained after optimization.

II.3 Experimental data and scenarios

The data used for the experiments includes the characteristics of JIRAMA’s Antananarivo Interconnected Network. This network provides information on bus configurations, generators, transmission lines and energy demand characteristics. The figure 3 shows the localization of the RIA network in Madagascar [13].

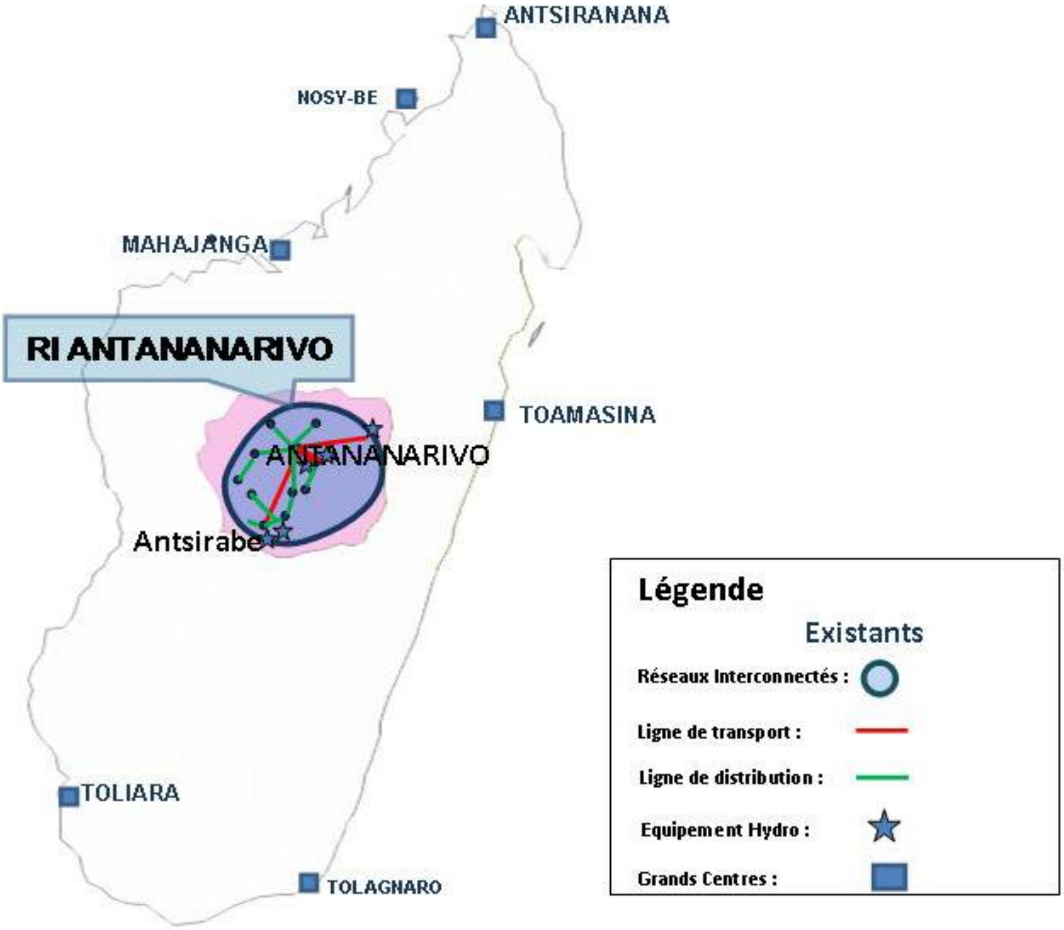

Figure 3 Localizationof the RIA network inMadagascar[13]

The experimental scenarios involve different use cases, taking into account, such as energy demand and sales variations, estimate based on hourly consumption profiles. After that, proportions of renewables energies with different levels of integration in the energy mix. Then simulation of disruptions and failures. Simulation results are analyzed to compare the performance of different optimization approaches and assess the impact on cost, resilience, social inclusion and energy transition criteria.

III. RESULTS AND DISCUSSION

Before proceeding with the analysis of the results, it is essential to define the parameterization of the algorithms and the configuration of the simulations used to optimize the energy system. The parameters of the MOPSO algorithm are adjusted according to the specifications of the optimization problem. These adjustments include the population size, which is set at 100 individuals, allowing sufficient exploration of the search space without incurring excessive computational costs, the number of iterations is 500, to allow adequate convergence towards optimal or near-optimal solutions [1], [3].

Secondly, crossover and mutation functions, i.e. for MOPSO, inertia and velocity parameters are adjusted to control the balance between exploration and exploitation. Simulation data include the characteristics of test networks with varying scenarios of energy demand, renewable energy integration and network disturbances. Simulations are run on this data in a computing environment capable of efficiently processing the calculations required to obtain the solutions [12].

The results of the algorithm are compared along two axes, i.e. with and without the optimization algorithms. The first analysis compares the performance of energy system configuration with and without the use of optimization algorithms. This comparison enables us to assess the direct impact of the algorithms on the results obtained in terms of costs, resilience and social inclusion and energy transition. In the scenario without optimization algorithm, planning decisions are based on traditional energy management approaches.The figure 4 illustrates the evolution of sales and demand form Office de Regulation de l’Electricite (ORE) data [13].

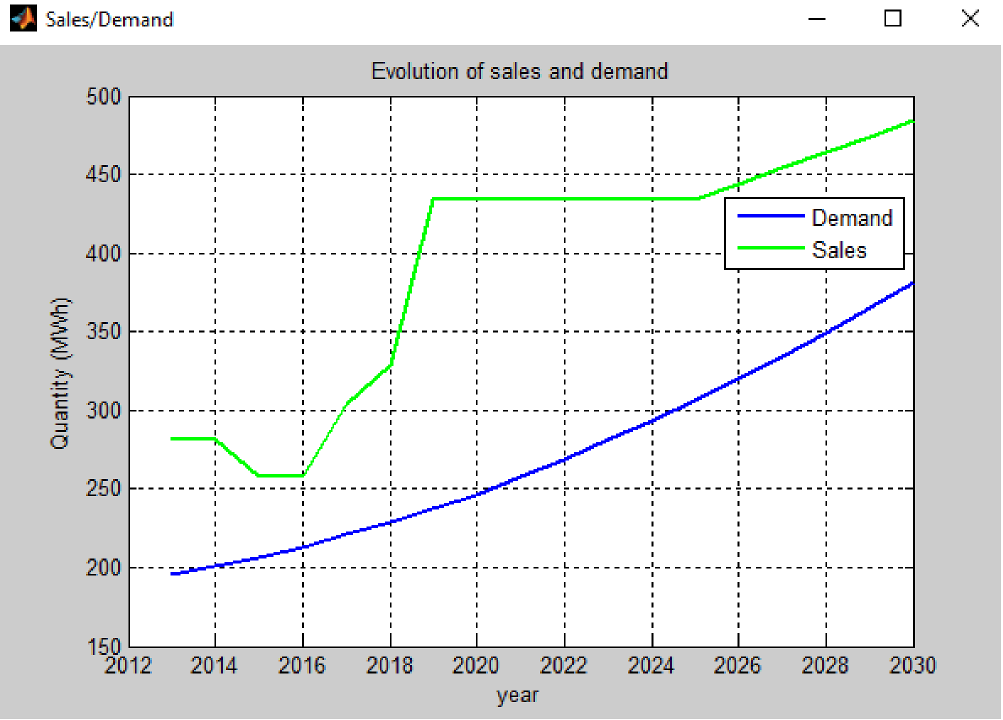

Figure 4 Evolution of sales and demand from JIRAMA

Figure 5 shows the tendency of evolution of hydraulic and thermal power. It means that it is better to encourage JIRAMA to use a renewable energies sources.

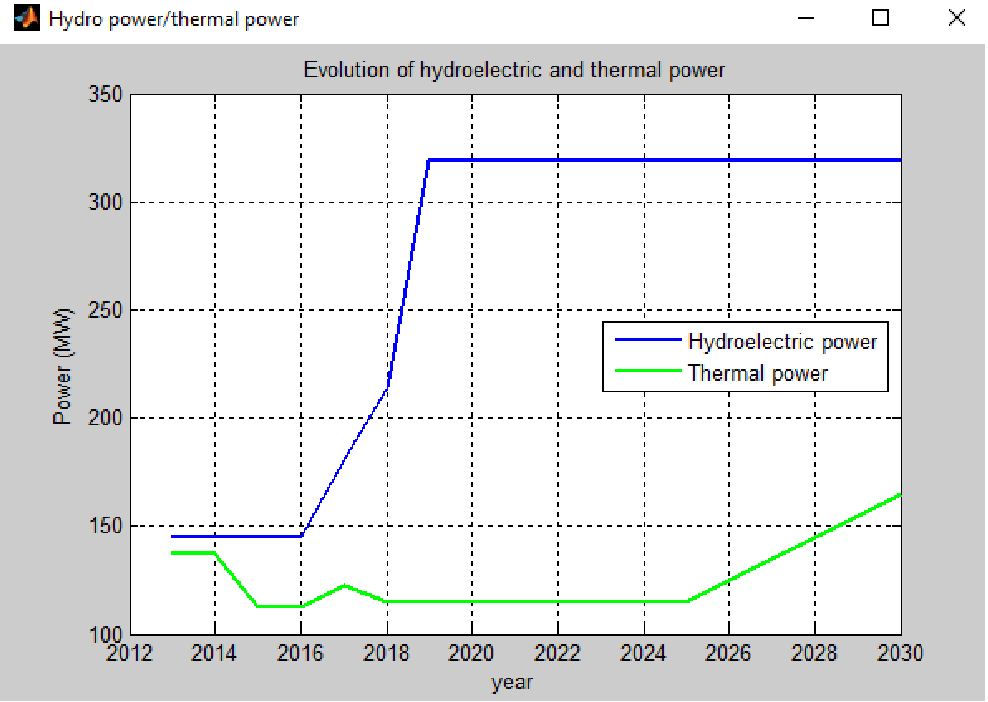

Figure 5 Comparison between hydraulic and thermal power

Figure 6 shows a comparison between evolution of production cost with and without optimization.

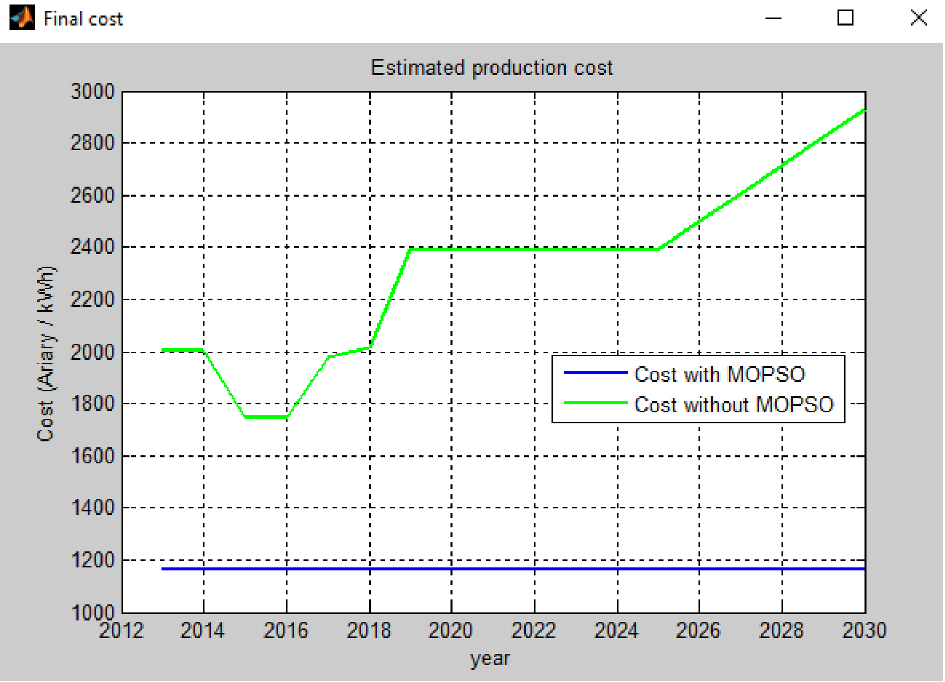

Figure 6 Comparison of cost with and without algorithm

Cost optimization is a key objective in ensuring the economic efficiency of the energy system. The results show that algorithm MOPSO showed a slight tendency to generate slightly more expensive solutions, due to its more exploratory approach.

Figure 7 shows energy system resilience and security. Network resilience is an essential criterion for ensuring continuity of energy supply in the face of disruptions.

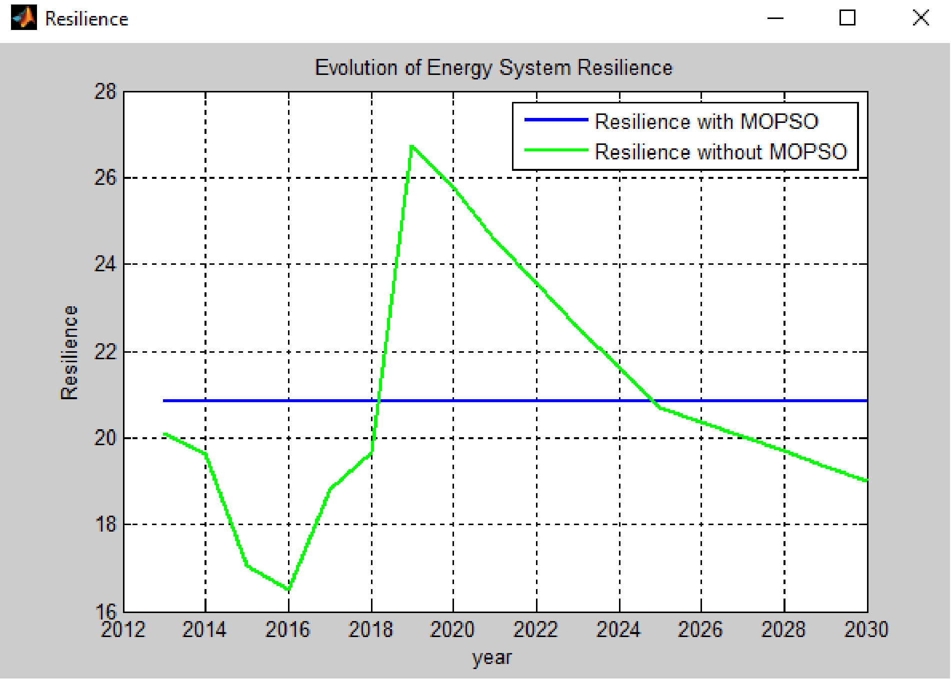

Figure 7 System's resilience

The results indicate that MOPSO has improved network resilience but it did not achieve the level of resilience in some extreme cases.

Figure 8 shows a comparison of energy transition with and without optimization and integration of renewable energies.

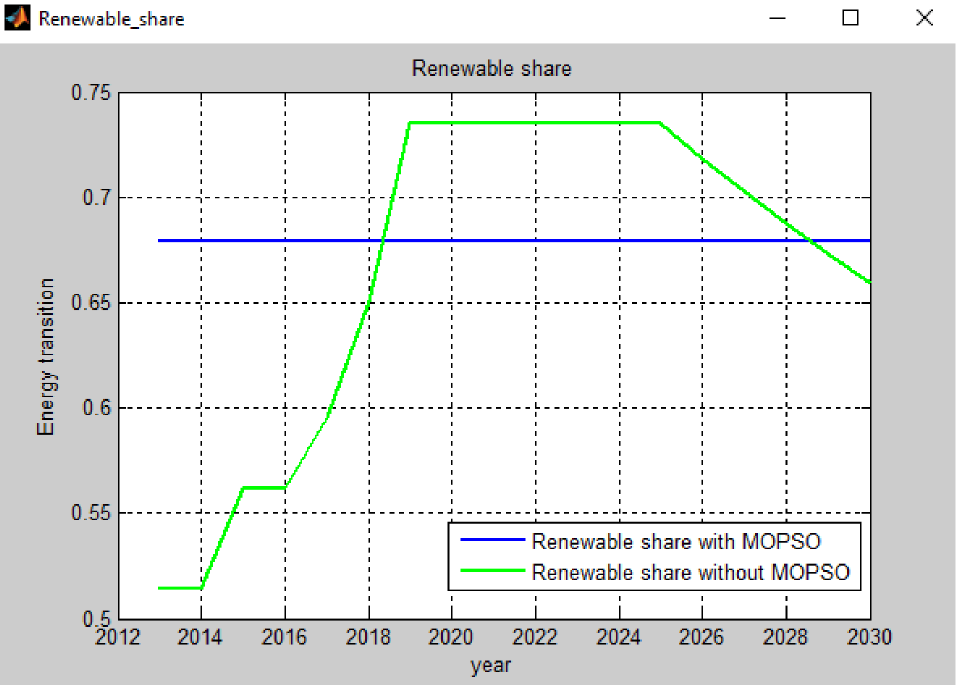

Figure 8 Energy transition

Energy transition is at the heart of the global decarbonization strategy. Algorithm MOPSO has demonstrated its ability to integrate a significant proportion of renewable energies.

Figure 9 shows the evolution of subscriber's number from 2013 to 2030. It displays social inclusion and energy accessibility.

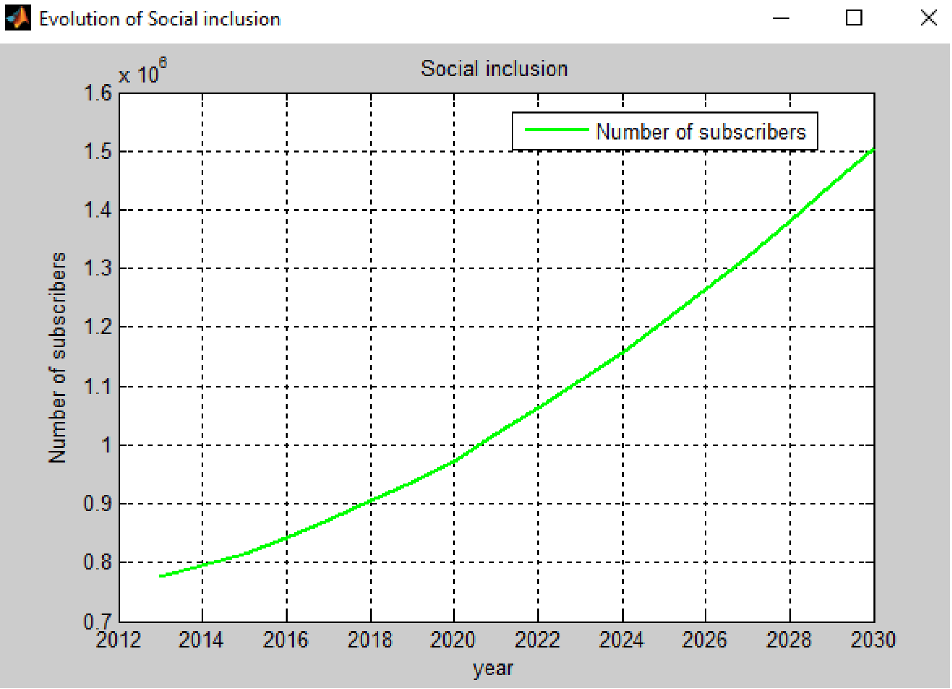

Figure 9 Social inclusion

Social inclusion, which includes equitable access to electricity for all, was a particularly important criterion for energy planning. The algorithm has enabled us to design solutions where the expansion of access to electricity has been maximized, while taking into account economic constraints. It is recommended to reinforce this dimension in future optimizations by integrating support policies for disadvantaged areas.

The MOPSO multi-objective particle swarm optimization algorithm shows good results in terms of rapid convergence and approximation to the Pareto frontier. It is particularly effective in managing trade-offs between different objectives and efficient exploration of the search space, useful for identifying a variety of solutions, flexibility in integrating different objectives and constraints, but sometimes presents difficulties in exploring the solution space as diversely as other methods. Its limits is about less effective for highly constrained or large-scale problems, which can affect its performance in more complex networks such as those in developing countries.

IV. CONCLUSION

This study explored the optimization of electric power generation through integrated planning, taking into account multiple objectives such as production cost, energy system resilience, social inclusion and energy transition. The approach was applied to JIRAMA's Antananarivo interconnected network in Madagascar. The result showed that the use of multi-objective optimization algorithms, namely MOPSO, enables efficient trade-offs to be achieved between different criteria, such as significant reduction in production costs while incorporating a higher proportion of renewable energies, second, significant improvement in network resilience, thanks to better management of disturbances and energy demand fluctuations, third, advances in social inclusion, making electricity more accessible, especially in rural and underserved areas, and finally, contribution to the energy transition, by better managing the integration of renewable energies into energy system.

The study makes a significant contribution to integrated energy planning by demonstrating the importance of a systematic approach that combines several key objectives for optimizing energy production. This research offers an overview of the challenges and opportunities in managing modern energy systems. Integrated planning, as explored in this study, goes beyond simple cost reduction by also focusing on social and environmental issues. This represents progress towards a sustainable and inclusive energy approach, capable of meeting the challenges of universal access to energy, while supporting the transition to renewable energy sources and ensuring greater resilience in the face of disruption. This research can serve as a basis for the elaboration of energy policies and sustainable development strategies in regions facing similar challenges like Madagascar. It also offers a methodological approach that can be used for energy modeling and planning in other geographical and economic contexts.

Future work must focus on several areas of improvement and further development, such as improving optimization for larger or more complex networks. This would include interconnected networks on a regional or national scale, where the challenges of coordination between different players and transmission and distribution constraints are more marked. They could also incorporate the environmental impact of energy choices and it would be appropriate to introduce climate forecasting and demand management models into optimization algorithms. Continued research on this subject will offer more robust and efficient solutions for a sustainable, equitable and resilient energy future.

REFERENCES

[1]. D. Kundur, N. Balu, et M. Lauby, Power System Stability and Control, 2nd ed. New York, NY, USA: McGraw-Hill, 2004.

[2]. X. Zhao et L. Wang, « Optimal power flow with renewable energy integration: A comprehensive review », Renew. Sustain. Energy Rev., vol. 81, pp. 1149-1164, 2018.

[3]. N. P. Padhy et S. Saini, « Optimal power flow control using evolutionary algorithms: A review », Int. J. Electr. Power Energy Syst., vol. 33, no. 2, pp. 231-244, 2011.

[4]. H. Lund et P. A. Ostergaard, « The Role of Energy Storage in the Transition to Renewable Energy Systems », Renew. Sustain. Energy Rev., vol. 38, pp. 205-214, 2014.

[5]. D. Sánchez et J. L. Sánchez, « Energy system planning: Integration of renewable sources and environmental considerations », Energy Policy, vol. 61, pp. 1141-1149, 2013.

[6]. UNDP, Powering the Future: A Global Perspective on Energy Access and the SDGs. United Nations Development Programme, 2017.

[7]. C. A. Coello, G. B. Lamont, et D. A. Van Veldhuizen, Evolutionary Algorithms for Solving Multi-Objective Problems. New York, NY, USA: Springer, 2007.

[8]. J. Kennedy et R. Eberhart, « Particle Swarm Optimization », in Proc. IEEE Int. Conf. Neural Netw., 1995, pp. 1942-1948.

[9]. B. K. Sovacool, « The Political Economy of Energy Transitions », Energy Res. Social Sci., vol. 52, pp. 35-42, 2019.

[10]. K. W. Ellis et J. P. Dietrich, « The resilience of power systems under climate change: A multi-criteria optimization approach », Appl. Energy, vol. 137, pp. 556-564, 2015.

[11]. IEA, World Energy Outlook 2020, International Energy Agency, 2020.

[12]. R. D. Zimmerman et C. E. Murillo-Sánchez, « MATPOWER: Steady-State Operations, Planning, and Analysis Tools for Power Systems Research and Education », IEEE Trans. Power Syst., vol. 26, no. 1, pp. 12-19, 2011.

[13]. JIRAMA, Réseau Interconnecté d'Antananarivo (RIA) : Étude et Développement, JIRAMA Madagascar, 2018.

[14]. J. Baker et N. N'Guessan, « Energy Access and Social Equity in Developing Countries », Renew. Sustain. Energy Rev., vol. 124, pp. 1098-1115, 2020.

[15]. UN, Progress on Energy Access and the SDGs, United Nations Report on Sustainable Energy, 2020.

[16]. V. Jain et A. Shukla, « A review on optimization techniques in power systems: The need for multi-objective optimization », Energy Rep., vol. 4, pp. 298-310, 2018.

[17]. A. Gorib et J. Wu, « Multi-objective optimization techniques in electric power systems planning », Renew. Sustain. Energy Rev., vol. 121, p. 109698, 2020.

[18]. S. Chakrabarti et R. Maiti, « A survey on multi-objective optimization techniques and their applications in energy systems », Energy Convers. Manage., vol. 198, p. 111898, 2019.

[19]. M. M. S. Mollah et A. Van den Bossche, « Sustainable energy planning with inclusion of social factors: A multi-objective optimization approach », Renew. Energy, vol. 141, pp. 741-757, 2019.

[20]. M. J. Hossain et M. K. Alam, « Energy transition and its impact on the resilience of the electric grid: A multi-criteria decision-making approach », Renew. Sustain. Energy Rev., vol. 68, pp. 758-773, 2017.

[21]. L. Ochoa et D. Callaway, « The Social Impact of Energy Transitions: Assessing the Role of Energy Access and Affordable Solutions », Energy Res. Social Sci., vol. 34, pp. 129-141, 2017.

[22]. M. Sullivan et L. Fuchs, « The Environmental and Social Impacts of Energy Optimization », Energy Econ., vol. 70, pp. 214-225, 2018.

[23]. M. Asif et T. Muneer, « Energy and Environmental Impacts of Energy Production Systems: A Review », Renew. Sustain. Energy Rev., vol. 41, pp. 2-10, 2015.