Long-term energy scenario ranking with MCDA analysis: the case of Reunion Island

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Abstract

Island territories rely heavily on fossil fuel resources, and transitioning to other energy sources is essential for their progress. To accomplish this, it is imperative to utilize local renewable energy sources. In this study, an analysis of energy planning for Reunion Island has been conducted where Multi-Criteria Decision Analysis (MCDA) methodologies have been used to evaluate the sustainability of energy scenarios for 2050. This evaluation is carried out considering criteria encompassing technical, economic, environmental, and social aspects of the scenarios. Further, perspectives of local actors were considered in the evaluation of these criteria. The results indicate that the greenhouse gas emissions and job creation criteria are considered to be of utmost significance, whilst technical criteria were regarded as the least significant by these local stakeholders. PROMETHEE II and TOPSIS MCDA analysis reveal that the Combined scenario, a scenario where all local energy resources are exploited to their maximum, is the preferred electricity generation scenario. The findings are used to formulate policy recommendations for island planners, helping them to adjust the island's current energy strategies. This study also serves as a valuable resource for other non-interconnected islands undergoing an energy transition.

Keywords: energy planning, MCDA, PROMETHEE II, TOPSIS, energy transition, electrical autonomy

1 Introduction

Island territories presently rely heavily on imported fossil energy resources. In response to the energy insecurity created by reliance on imported fossil fuels, their depletion and their effect on climate, the transition to alternative energy sources has become essential for the sustainable development of remote islands. The successful transition of islands heavily relies on the effective planning of new resources distributed throughout these territories, some of which are intermittent [1]. Due to this, new infrastructures must be carefully planned, requiring a comprehensive evaluation of their technical, economic, environmental, and societal impacts.

To this end, energy planning for island territories has been extensively studied in recent years [2]. A technical point of view has mainly been adopted to investigate 100% renewable production energy on an island. To this end, different tools have been developed to scale various energy production technologies [3]. Bottom-up energy models such as EnergyPlan [4], TIMES [5], OseMOSYS [6], H2RES [7], LEAP [8], and UC-Plexos [9] among others, have been used to study the technical feasibility of energy scenarios on islands. A power system analysis for Reunion Island using TIMES has been proposed, emphasizing the importance of flexibility solutions to achieve the 100% renewables target [10]. According to [11], open-source tools such as OseMOSYS and PyPSA are mature enough for serious use. In considering unit commitment with optimal power flow, PyPSA could be considered the best choice.

Energy scenarios generated from those tools are commonly evaluated according to technical and economic criteria [12,13]. Nevertheless, additional factors must be considered when assessing the sustainability of scenarios, for which there are different approaches. One of them is the integration of social and socio-technical characteristics of energy systems in scenario design, along with using techno-economic and ecological indicators for scenario analysis. The social dimension can be included by using qualitatively or quantitatively measurable indicators such as social acceptance, job creation, social benefit, and human health [14-16].

Multi Criteria Decision Analysis (MCDA) methods are frequently used for sustainability assessment of energy systems, which requires a range of indicators from the economy, environment, and society pillars [17]. MCDA analysis improves the decision-making process in energy planning by providing decision recommendations such as ranking, sorting, selecting, and clustering of alternatives [18]. It has been employed to identify the best compromise energy scenarios, from small all the way up to large regional scales. This range includes analyses for households [19], building blocks [20], small communities, including energy communities [21], regions, including islands [22,23], specific countries [24,25] and even greater geographical areas or group of countries [26]. In such research, it is quite commonly implied that, irrespective of the scale of the analysis, the development of real applications with actual policymakers that would conclude on appropriate energy scenarios is of vast importance. These applications of MCDA methods encompass the entire decision-making process from the definition of objectives to alternatives development, criteria establishment, criteria evaluation, Decision-Makers (DMs) inclusion, selection of MCDA method(s), criteria weights' elicitation (DMs preference modelling), running of the decision model, sensitivity analysis, results inquiry, iteration and feedback and finally policy development. Further, this process should take place in a collaborative participatory planning setting.

Regarding islands' energy systems, MCDA along with input from local stakeholders, have been used to assess and rank potential energy systems considering social perspective on land use change impact for the Faroe Islands, a small-density population island [27]. On the island of San Andrés in Columbia, MCDA was used to assess different short-term energy alternatives considering experts' opinions [28]. A MCDA approach has been used to identify the best scenario for Sri Lanka

[29], an island with an equivalent density population as La Reunion but with less proportion of protected natural area. Stakeholders are surveyed only for social acceptance indicator assessment. Hypothetical ones are considered for criteria weighting.

This paper contributes to the design, development, implementation, interpretation of results, and analysis of an applied MCDA case study for energy planning to achieve an autonomous and semi-autonomous electricity grid, i.e., geographical islands or ‘energy islands’ in the mainland. Specifically, the case study is applied to La Reunion, a French overseas island. The standard steps of MCDA studies have been followed with tailored proposals of how to model each step in real life for such energy systems. This involves the consideration of pertinent methods for energy scenario development following the relevant regional policy aspirations and grid situation, decision criteria establishment with explicit directions of preference, and criteria evaluation with newly developed indicators and a mix of quantitative and qualitative metrics. Furthermore, the actual stakeholders were included in the decision-making process and expressed their preferences on the decision criteria through the modelling of their criterion weights. Two distinct MCDA methods have been applied and the comparison of the outcomes together with an extensive sensitivity analysis has increased the robustness of the results which were finally used for policy development. Three long-term energy scenarios derived from [30] and a new one are considered to achieve electrical autonomy with renewable energy for Reunion Island by 2050. These scenarios are then ranked using MCDA methods with input from key local stakeholders on core planning criteria. A new criterion is proposed to evaluate land use conflict in this highly constrained territory as a social criterion. The results of this ranking and comments from the local stakeholders are used to develop a set of new policy recommendations for planners. The analysis could also complement other studies that lift the relevance of demand response and smart energy systems on islands [31-34]. Taken as a whole, the overall methodology used in this paper and the results of this work are valuable to other highly populated islands with environmental constraints as they seek to calibrate their current energy plans to achieve independence.

The paper is structured as follows: Section 2 describes the energy transition of Reunion Island before introducing the newly designed 2050 energy scenarios. Section 3 describes the MCDA methodology, along with the criteria used to assess the generated energy scenarios and the survey of local actors. Section 4 presents and discusses the results of the MCDA analysis. Section 5 further deliberates the policy implications of the MCDA results for the island’s current energy planning and gives policy recommendations. Finally, conclusions are made in Section 6.

2 Energy transition in Reunion Island and the future scenarios

Islands’ energy transition constitutes a response to the climate crisis, a diminishing energy security and high energy costs due to a dependence on imported fossil fuels from the mainland. These energy transition goals for islands are expanded on for the island of La Réunion and the various paths it can consider to tackle them are detailed in this section.

2.1 Energy transition in Reunion

Reunion is a distinctive European island between Madagascar and Mauritius in the Indian Ocean. Like many other non-interconnected islands, it has energy supply issues. Demographic, economic, and societal changes have boosted the island's fossil fuel imports since the early 1980s but, since 2000, investments have been made in different renewable energies to try and move away from fossil fuels. Buildings and transport represent almost 90% of the island's energy consumption. Then, the major challenge for energy transition is to provide decarbonized electricity. However, as of 2022, electricity production was still predominately generated from primary fossil energies (coal and oil) and only 37.7% was generated from renewable energies, essentially hydropower (21%), biomass (6%), and PV (8.7%) [35]. Thanks to the conversion of a thermal power plant in 2024, Reunion Island will be close to achieving 100% renewable electricity generation by replacing imported coal and diesel with imported wood pellets and liquid biofuel. Despite the likelihood of achieving 100% renewable power generation in the coming years, Reunion Island is still far from electrical energy self-sufficiency as a large part of biomass it will use will be imported - in 2022, the region's energy was generated 85.8% from imported sources [35].

2.2 The 2050 energy scenarios

This section describes the main assumptions related to the energy system and the new scenario investigates.

Regarding assumptions, this study excludes the energy requirements of maritime and air transport sectors. For the last one, the actual amount of kerosene consumption is 2,481 GWh [35] resulting optimistically in at least 6,840 GWh of electricity consumption to make e-kerosene for air transport alone [36]. As this amount is twice the island's current electricity consumption for the year, it has been considered unfeasible with current technologies, and only electricity consumption for local use is being taken into account.

The scenarios are developed considering an annual electricity consumption of 4,130 GWh. This value is comprised of two components. Firstly, base load consumption, which amounts to 3,080 GWh. This consumption is taken from scenarios for 2030 in [37] assuming a particular level of improvement in energy demand management and energy efficiency, with electricity demand increasing by 1 %/year between 2015 and 2030. For comparison, this demand was 2,820 GWh in 2022 [35]. Since no projections are available for 2050, this base annual consumption value is adopted assuming even greater deployment of energy efficiency associated with the electrification of uses. An additional 1,000 GWh has been added to this baseline consumption, corresponding to the additional annual electricity demand if the vehicles making up the private car fleet were converted to electrical [37]. This consumption has been evaluated assuming an optimistic integration of electric vehicles into the grid, optimising charging to primarily take advantage of photovoltaic power using advanced demand management systems.

The Base, Intermittent, and Combined scenarios are derived from prior research [30]. A new scenario called Optimised is introduced. In this study, the capacity of power-producing facilities to reduce installation and operational costs is optimised. Revised operational costs have been taken from [37-39]. The optimisation exploits the maximum limits for the various technologies derived from the Combined scenario. The minimum limits represent the capabilities now installed on the island. To simplify the optimisation problem, OTEC technology has been eliminated due to its underdevelopment, and geothermal technology has been constrained to either 0 MW or 15 MW, corresponding to the capacity of a single power plant. This scenario illustrates the situation in which minimising construction costs is the foremost consideration for the development of the island's electricity system. As a result, the Optimised scenario has the smallest installed power capacity and the Combined scenario the highest (Figure 1).

To evaluate the technical feasibility of the scenarios, simulations of the Reunion Island electrical system have been conducted for 2050 with an economic dispatch optimisation for the different scenarios [30]. The considered variables are, the nominal battery capacity, the hourly management of their dispatch and stored energy, as well as the scheduling of power generation technologies, and potential enhancements to high-voltage transmission lines. Simulations demonstrate that in the Optimised scenario, biomass generates a greater amount of energy compared to other scenarios to compensate for the lower energy production from PV and hydropower (Figure 1). The Combined scenario, including PV and hydropower, significantly minimises biomass energy output.

	Base	Intermittent	Combined	Optimised
PV	1,200	1,200	1,200	939
Hydropower	200	200	233	238
Onshore wind	100	146	146	146
Offshore wind	0	40	40	0
OTEC	31	0	31	0
Geothermal	15	0	15	15
Biomass	320	320	320	319
Total	1,866	1,906	1,985	1,657

Table 1: Installed power capacity (MW) for the investigated energy scenarios.

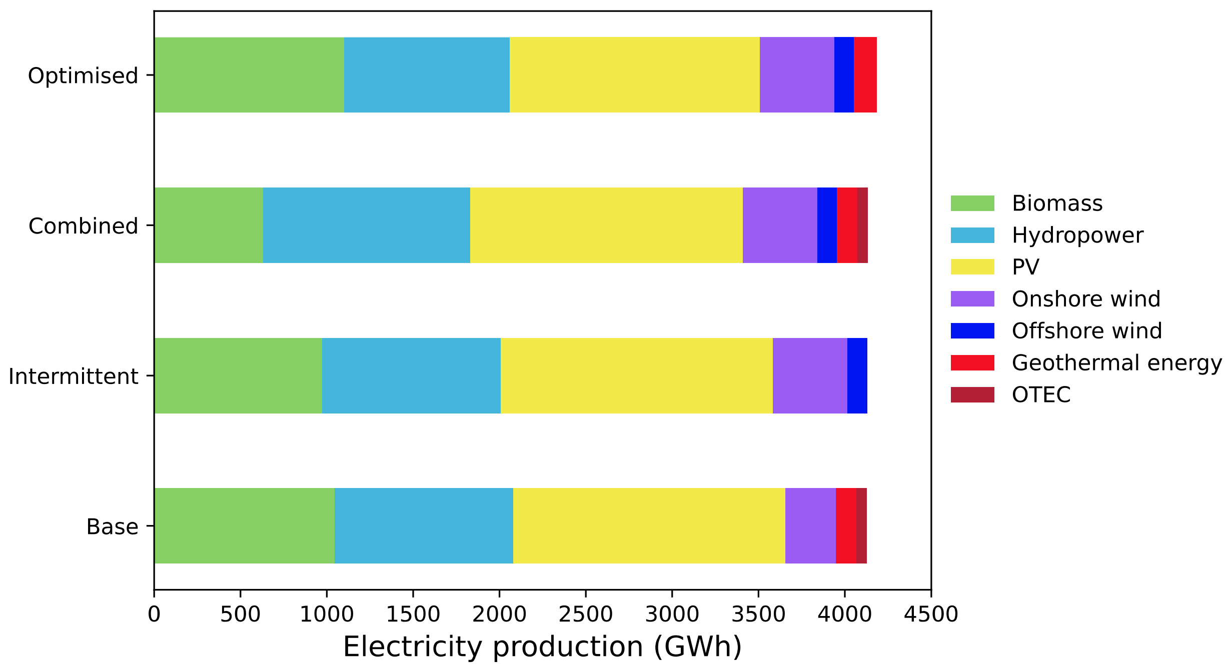

Figure 1. Annual electricity production (GWh) shares by production type for the investigated energy scenarios.

3 Application of the Multi Criteria Decision Analysis

This section presents the methodology employed in the study, focussing on the criteria selected for the MCDA and the method used to obtain their weights.

3.1 MCDA Methods

MCDA is used to assist decision-makers when more than one criterion needs to be evaluated simultaneously for different potential plans or options. MCDA allows for creating a framework that can gather, order and analyse the relevant information for making a decision [40]. MCDA has been used to assess specific energy projects on islands [41,42] as well as larger changes to island energy systems and policy [27,29,43,44]. The four scenarios for Reunion Island have been comparatively assessed using two MCDA methods, PROMETHEE II and TOPSIS. Both methods have been regularly used in analysing energy production and system performance [27,43,45]. Several comparative analyses on the appropriateness of MCDA methods to energy and environmental planning and policy selection problems have been conducted for many decades [46-50]. The outranking methods like the ELECTRE and PROMETHEE families of techniques are consistently ranked among the most suitable for such public decision-making. At the same time, the more recently developed TOPSIS method has been widely applied in the same domain as a valuable alternative [51]. That said, it is commonly agreed there are no better or worse techniques, only techniques that can fit better in certain situations. Other methods developed to address perceived shortfalls could have also been utilised to perform the assessment such as ESP-COMET, SPOTIS, or SIMUS, though even these have shortcomings [52-54]. In fact, the selection of a MCDA method for a decision analysis challenge is a multi-criteria decision problem on its own and tools have been developed to help decision-makers accordingly [55,56]. The weights used for the assessments were obtained from relevant local stakeholders as described in Section 3.3.

3.2 Criteria for MCDA

The eight selected criteria for the MCDA fall into the four primary categories typically covered in the evaluation of energy systems - technical, economic, environmental, and social [14]. Each category is represented by a pair of criteria, explained in the sections. These criteria have been chosen with consideration for factors such as data availability, data quality, and the need to encompass a broad spectrum of sustainability concerns.

3.2.1 Economic impact

The four scenarios' capital costs (CAPEX) and the electricity production costs (OPEX) are calculated to determine economic impacts. CAPEX includes the cost of grid line reinforcement in addition to the cost of generation units, batteries and their installation. The data used for the CAPEX calculations is derived from [30]. Operation and maintenance (O&M) costs include a fixed and a variable component. Values for technologies already installed on the island are taken from [37]. For those not yet deployed, costs are taken from [38,57] and considered the same for the year 2050. Different biomass conversion methods have been considered to account for the substantial variation in cost between technologies.

3.2.2 Environmental impact

The environmental impacts of the scenarios were evaluated using the scenarios' water consumption and life-cycle greenhouse gas (GHG) emissions. The values for each energy production technology in the scenarios are identical to those employed in [30]. For the batteries, the value of 330 $kgCO_2/MWh$ is used in the present study [58]. Due to the limited availability of water on the island, its use is considered in the four scenarios through a criterion measuring the water withdrawn from the environment by the power plant during its construction and operation, without being returned to its original source [59]. Water consumption data for solar PV, hydropower, biomass and onshore wind were found in [59]. Solar photovoltaics is the only technology for which local water use is zero during operation.
Life cycle emissions of GHG, which include CO_2, CH_4, and NO_2 emissions, measured in CO_2 equivalents from upstream activities' (i.e. manufacturing, construction, and mining), O&M, and downstream activities' (i.e. decommission), were taken from [59].

3.2.3 Technical impact

Batteries are required to integrate intermittent renewable energy sources in the electrical mix. An optimization has been conducted based on the production technology capacities set for each scenario to determine the necessary battery capacity which minimizes both investment and operating costs while also meeting the hourly energy demand [30]. Optimising factors include battery storage size at each grid substation, hourly electricity mix, and grid reinforcement. The installed power scenarios are input data to limit hourly electricity generation and simplify the model, except in the Optimised scenario in this work, where they are also optimisation variables. Standard constraints of the optimisation problem include nodal power balances at each substation, storage sizing employing flows and standing losses, and electrical production facility sizing in the Optimised scenario.

The integration of intermittent renewable energies, in particular photovoltaic and wind power, represents a challenge for the management of a non-interconnected electricity network. The proportion of intermittent energy that cannot be dispatched and has little or no inertia can be an indicator of the robustness of the power system. As a result, in this work, under the same management system, a lower percentage of intermittent energy implies a stronger power network.

3.2.4 Social impact

Combined social impact score. Reunion Island is a densely populated island of 2,512 km^2 and a biodiversity hotspot, with almost half of its territory being natural areas. The amount of land available for energy production facilities can represent an obstacle to the development of certain technologies, as can acceptance due to Not In My Backyard conflicts. To deal with this, a criterion is proposed in this work. This criterion combines four sub-criteria: land requirement, land use conflict, noise and visual impact. The first two are evaluated using quantitative methods, while the final two are assessed qualitatively. Noise and visual impacts are considered as these could affect the social acceptance of the scenarios [27,60]. Given its composite nature, it provides a magnitude rating from low (1) to high (3) for each scenario.

The land requirements were selected as a sub-criterion due to the limited availability of this resource on the island. On Reunion Island, more than 40% of the territory is a protected area with a strong interest in biodiversity and the development of agriculture could compete with the energy sector and urbanization [61]. In this context, land use can lead to potential conflicts, and the requirements are calculated by considering all the land within the power plant site boundaries. This includes direct land uses for power plant installation and indirect land uses for facility buildings and access roads. These lifetime land requirement values are taken as the maximum life cycle land use of power plants, measured in terms of m^2/MW, from [59]. The area per technology for a given scenario is considered. The magnitude for this technology is set according to the scale given in Table 2. The land requirement magnitude for a given scenario is calculated by the arithmetic mean of the technology magnitudes.

Magnitude	Scale
0	0 km²
1	< 1 km²
2	1 < x < 10 km²
3	> 10 km²

Table 2: Scale used to define the magnitude of the land use requirement for a technology.

The competition with other land uses is considered with the land use conflict sub-criterion. In this study, a scale assessment is proposed based on the renewable resources and land use maps and on local experts' interview (Table 3). The development of any onshore production technology on the island is expected to be more problematic. The expansion of hydropower is limited because the most exploitable resources are already being used and the other areas with significant resources are located within environmentally protected areas. Onshore wind faces significant constraints due to non-uniform wind resources and restrictive zoning legislation. The use of agricultural land for biomass energy generation is highly controversial [61]. The island's primary geothermal resources are also located within environmentally protected areas. Additional solar PV should primarily be integrated onto buildings, with only 8% of the installed capacity being located on the ground, to limit potential conflicts with other land uses. The implementation of agrivoltaics may alleviate conflicts with agriculture; however, the extensive adoption of this solution remains contingent upon uncertainties related to its landscape effects and the agricultural production model in tropical regions vulnerable to cyclonic hazards [62,63], such as Reunion Island. The exploration of offshore sites will make it possible to reduce land-use conflicts.
The noise and visual impacts are addressed by a literature review conversely to the land use conflict sub-criterion. The different technologies' impact magnitudes are derived from [60, 64-67] and are given in Table 3. For OTEC, the impacts are considered equivalent to those of offshore wind. The visual impact of geothermal is deemed high for Reunion Island due to the resource's location in a nature reserve.

	NOISE	VISUAL	LAND USE CONFLICT
PV	1	2	2
HYDRO	1	2	3
ONSHORE WIND	2	2	3
OFFSHORE WIND	1	1	1
BIOMASS	2	2	3
OTEC	1	1	1
GEOTHERMAL	2	3	3

Table 3: Technologies magnitude order of noise, visual, and land use conflict

Each impact magnitude (noise, visual and land use conflict) for each scenario is set from the total magnitude as calculated by the following formula:

$$IM_{l,j} = \sum_i n_{l,i} \times P_{i,j} \qquad (1)$$

with $IM_{l,j}$, being the total magnitude of the impact l for the scenario j, $n_{l,i}$ the magnitude order of the impact l for the technology i, $P_{i,j}$ the capacity of the technology i for the scenario j.
The impact magnitude is assessed in relation to the total magnitude of the different scenarios. The maximum value is set at 3, the minimum at 1 and the average at 2. The combined social impact score for a scenario j is the arithmetic mean of the different sub-criteria magnitude.
The developed criterion is straightforward, easy to understand, assess and integrate at the MCDA policy analysis exercise. That renders it highly valuable in the real arena of policy making and it has been developed in collaboration with local stakeholders from La Reunion island that have also contributed to its relative assessment among the scenarios. In that way, the actual content of policy

development is taken into consideration and the results are agreed and communicated to the stakeholders and decision-makers directly.

Job creation. Direct job creation is calculated using employment factors for each considered energy production technology as found in [68], where the values in Organisation for Economic Co-operation and Development (OECD) Europe are used. Only direct employment is included, namely jobs in construction, operations, and O&M as none of the technologies considered in the scenarios can be manufactured locally on Reunion. Additionally, the construction and installation job factors from these sources were standardized to jobs per installed capacity following the method used by [69]. Using this method, the job-years per installed capacity employed in a technology's construction provided by [68] were multiplied by the ratio of total construction time to the technology's useful life, as taken from [70]. The results range from 0.1 to 0.7 job/MW, comparable to [27,70,71]. In other research, detailed analyses have been conducted to estimate the local job opportunities that can be generated through the renewable energy transition of coastal and coastal island cities [72].

3.3 Survey of local actors

On Reunion Island, energy planning is based on the work of a group of experts from institutions in the fields of energy and the environment. Six major stakeholders who have contributed to recent planning exercises were contacted to provide their inputs. Actor 1 is a mediator and Actor 2 is a regulator in energy and environmental policies. Actor 3 is a regulator and an investor in electrical energy. Actor 4 is a mediator in energy policy. Actor 5 plays the role of governance and investor in energy policy. Finally, Actor 6 is a producer/supplier. These different Actors were questioned about the relative importance of the different criteria noted above when they are assessing an energy transition scenario. The criteria were presented to the actors and they were to weight these criteria by allocating a fixed number of points (100) amongst the criteria. A higher point score on a given criterion indicates that the criterion has greater importance to the stakeholder [73]. The meaning of weights in MCDA has been greatly discussed and different MCDA methods demand different types of weights [74-77]. At the same time, a number of weight elicitation techniques have emerged that serve multiple purposes [78,79]. Different weight elicitation methods could have been used here, however a straightforward, easily understood technique was used to reduce the cognitive burden of the stakeholders. These stakeholders also gave explanations for their reasoning in providing the weights they did for each criterion.

4 Results and discussion

The findings in this section encompass the evaluation of criteria for each scenario, the assessment of the criteria weights, the ranking of scenarios using the two MCDA methods and the sensitivity analyses on those rankings.

4.1 Criterion scores

The score for each criterion is presented in Table 4. Regarding the environmental criteria, the Combined scenario performs the best. This is due to the lowest biomass production, as GHG emissions and water consumption are mainly driven by biomass technology (35 tCO_2/GWh and 553 m^3/GWh). Despite the highest cost of facilities, the Combined scenario has the cheapest electricity production cost and generates the most jobs while also having the highest Combined social impact score. As this scenario considers power generation through the utilization of all the available resources to their maximum, the required labour force and the social impacts are the highest. The electricity production cost for the Optimised scenario is related to biomass production and remains below the Base scenario but above the other scenarios. From this, it appears that biomass production significantly impacts environmental and economic criteria, whereas PV capacity has more impact on job creation and technical criteria.

		Base	Intermittent	Combined	Optimised	Unit	Preference
Environmental	Life cycle GHG / year	37	35	23	39	$ktCO_{2eq}$	Min
	Water consumption	7.36e5	6.37e5	5.09e5	7.54e5	m^3	Min
Economical	Facility capital cost	5.05	4.85	5.51	4.18	Billion €	Min
	Annual electricity production cost	205.8	180	138	199.2	M€	Min
Technical	Battery requirements	1680	2157	2180	1020	MWh	Min
	Percentage of intermittent resource	69.7	72.7	69.8	65.5	%	Min
Social	Job creation	722	747	772	652	Jobs	Max
	Combined social impact score	1.893	1.857	2.678	1.107	Magnitude (1: low; 3; high)	Min

Table 4: Criteria summary of the 2050 scenarios based on consumption scenario with energy efficiency improvement.

4.2 Stakeholder weights

The weights provided by each stakeholder are given in Table 5. They have been obtained through an iterative process including an online survey and regular interactions to confirm the weight assessment.

Criteria	Sub-criteria	Actor 1	Actor 2	Actor 3	Actor 4	Actor 5	Actor 6	Average
Environmental	Life cycle GHG emission	40	5	20	25	25	25	23
	Water consumption	25	10	2	10	0	5	8
Economic	Facility capital cost	5	15	15	15	20	20	15
	Electricity production cost	5	15	15	15	20	10	13
Technical	Battery requirement	0	15	5	5	10	5	7
	Percentage of intermittent production	0	10	10	5	5	10	7
Social	Job creation	25	15	18	15	10	10	16
	Combined social impact score	0	15	15	10	10	15	11

Table 5: Criteria summary of the weights given by the stakeholders interviewed.

Analysis of the stakeholders' comments showed that they largely align with the weights they provided. Actor 1 emphasized the environment (65 out of 100 points), with GHG emissions at 40 points and water consumption at 25 points. They also placed heavy emphasis on the creation of jobs (25 points). Though the other actors were less focused in their weighting distributions, the environmental criterion of GHG emissions was, on average, deemed the most important (23 points), though not far more so than the job creation and the economic criteria. Conversely, the technical criteria were deemed by a large margin to be the least important. Should Actor 1's weightings be removed, the economic criteria become the most important while social and environmental have similar average weightings. These findings are consistent with those of [28], for which GHG emissions and job creation are among the most important sub-criteria according to the experts.

The stakeholders' weighting explanations clarify their preferences. Actor 1, a mediator, explained that the environmental criteria were most important as they were the cause of global social and economic issues. Actor 1 also believed that neither the economic nor technical criteria were significant issues, but merely prioritization problems. Actor 2, a regulator, placed the least emphasis on the environmental criteria and most on the technical, felt the criteria of GHG emissions was too crude a measure of environmental impact while also emphasizing that the energy mix to be used was a technical and economic decision. Actor 2 also noted that there was a missing technical criterion relating to island energy autonomy, a primary goal of the island. All Actors, except Actor 1, placed significant emphasis on the economics of the project. Actor 5, a governance/ investor, emphasized that economics are directly linked to making a system possible and ensuring its sustainability. They also emphasized the link between economic and social impacts through job creation, which Actor 1 also noted as being important despite their de-emphasis on the economic criteria.

4.3 MCDA Results

The results of the application of the PROMETHEE II and the TOPSIS MCDA methods are presented and discussed as follows.

4.3.1 PROMETHEE II

The results of the PROMETHEE II analysis net flows, or the aggregated scores for all included criteria, of each scenario for each Actor are shown in Figure 2. In addition to the net flows using the Actor weights, two additional net flows are included where an equal weighting for each criterion is used as well as the net flows found by using the average Actor weighting for each criterion. These two additional net flows are called Equal and Averaged Score, respectively. The higher a scenario's net flow value, the higher it is ranked.

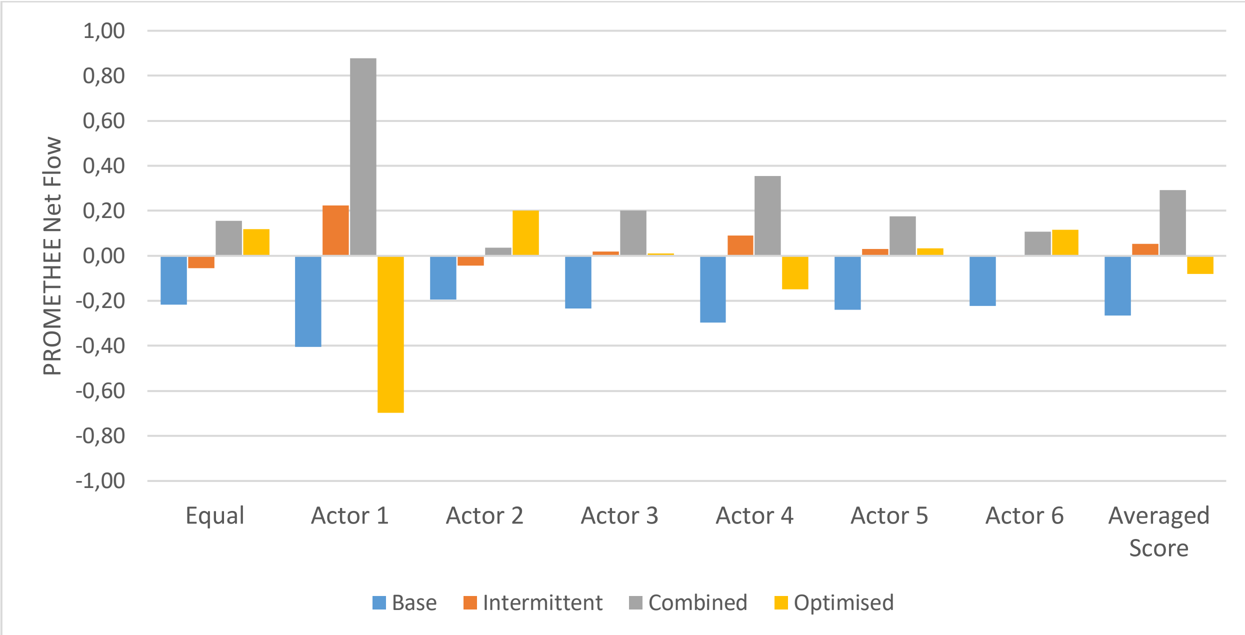

Figure 2. PROMETHEE II scenario net flows.

As shown in Figure 2, there is no clear agreement between the Actors. Actors 2 and 6 preferred the Optimised scenario while the other Actors preferred the Combined scenario. Actor 1 had the strongest preference for the Combined scenario while Actor 6 was nearly indifferent between the Combined and Optimised scenarios. Neither the Base nor Intermittent scenarios were preferred by any Actor, though the Base scenario tended to be the lowest ranking scenario. The Intermittent scenario, however, ranked second for two of the Actors.

4.3.2 TOPSIS

The results of the TOPSIS analysis, performance scores obtained from each criterion's distance from the positive and negative ideal solutions for each scenario, are presented in Figure 3. The scenarios are ranked based on higher performance score values.

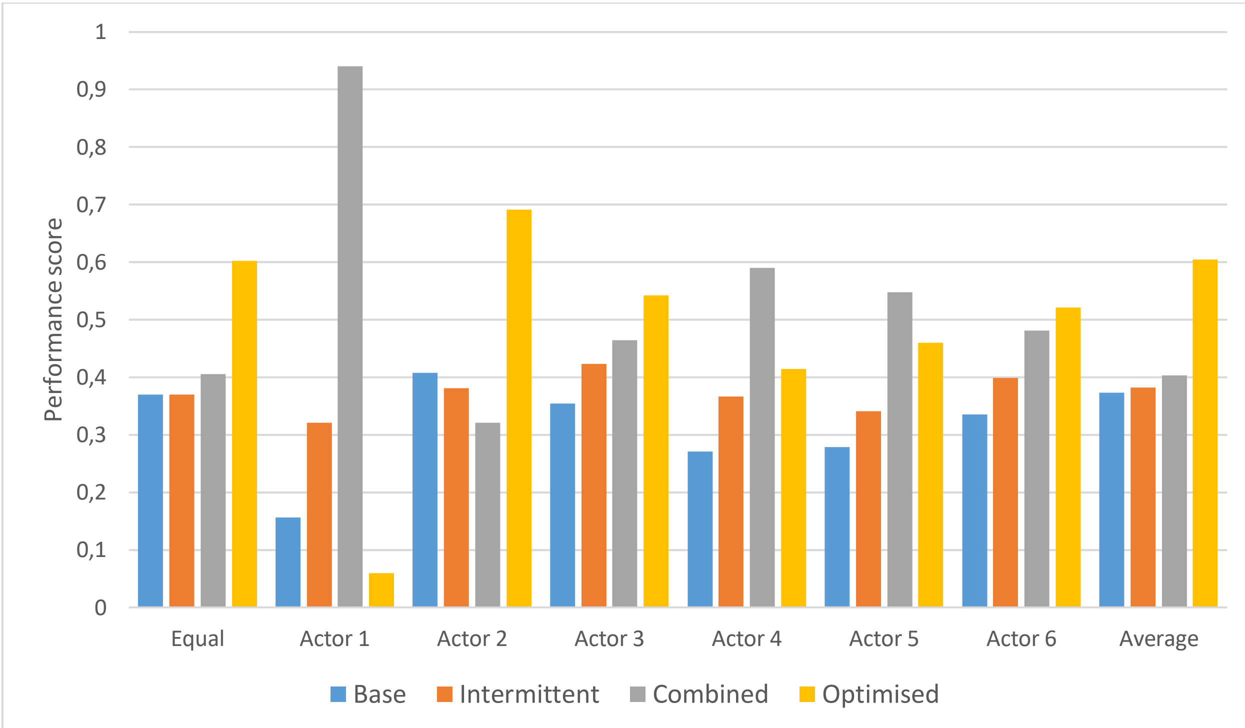

Figure 3. Scenario TOPSIS performance scores

Using the TOPSIS MCDA method, three Actors prefer the Combined and three prefer the Optimised scenarios. As with the PROMETHEE method, the strength of the preferences using Actor 1's weights result in a strong preference for the Combined scenario while Actor 6's weights result in relatively close performance scores between the Optimised and Combined. The Base scenario tended to be the least preferred option while the Intermittent scenario ranked third for each Actor except Actor 1.

4.3.3 Comparison of MCDA results

The two MCDA methods are largely in agreement for their indications of preference for the Combined and Optimised scenarios. All Actors except Actor 3 maintained their favoured scenario between the two methods, while Actors 2 and 4 saw some other ranking changes. A closer look at the differences for Actor 3 finds a notable increase in the performance of the Optimised scenario when comparing the TOPSIS method to the PROMETHEE II. Examination as to why this occurred reveals that it is a result of their underlying criterion performance aggregation methodologies. The TOPSIS method allows for full compensation, meaning that performance on one criterion can fully offset performance on another, while PROMETHEE II is a low compensation method, meaning performance on one criterion can only partially offset performance on another [46,80]. TOPSIS's compensation allowance results in the Optimised scenario's better performances to offset its poorer performance on other criteria. Sensitivity analyses were performed on the results obtained from the two MCDA methods by varying the criteria weights. The weights were incrementally adjusted to change weighting emphasis between the different criteria to evaluate the overall impacts on rankings. The weight for the Water Consumption criterion was assigned a value of zero, with the remaining weight evenly allocated to the other criteria. The weight of the Water Consumption criterion was gradually increased, while the weights of the other criteria were correspondingly reduced. The analyses indicated that the results were consistent across both methods, with the Optimised and Combined scenarios being favoured over the Base and Intermittent. The Intermittent scenario outperformed either the Optimised or Combined scenarios, dependent upon the weighting emphasis, but not both simultaneously. A comprehensive comparison of the results obtained from the two MCDA methods necessitates further sensitivity analysis to evaluate the study's robustness against variations in methodological assumptions, thereby increasing confidence in the findings [81-83].

4.3.4 Discussion of MCDA results

The results of the MCDA analyses give a mixed picture of which scenario is preferred by the Actors, Combined or Optimised. Neither of the two scenarios stands out as being preferred overall, though Combined might be said to be slightly more so with the PROMETHEE II method. Then, the social criteria give a mixed ranking of scenarios and does not favour a specific scenario, unlike in [27] where a clear social preference for offshore scenarios is exhibited. Actor 1's heavy weightings towards the environmental criteria present a clear result that remains the same between the two methods, while Actor 6's more balanced weighting of the criteria provides a much closer ranking between the two top-ranked scenarios. The other two scenarios, Base and Intermittent, are not preferred by any of the Actors in either of the methods, though the Intermittent occasionally performed better than either the Combined or Optimised. The Base scenario largely was the least preferred, with only a single instance where it ranked second in either of the methods. These results are not readily apparent from the scenario criteria scores shown in Table 4, where both the Combined and Optimised scenarios perform best on four of the sub-criteria and worst on three of them.

Comparing the results to the weights and to rationale provided by the Actors confirms the results, most evidently for Actor 1 who placed well over half of their weight on the environmental criteria. The Combined scenario performed best on these criteria while the Optimised performed worst. Further, Actor 1 placed significant weight on the creation of jobs where again the Combined scenario performed the best and the Optimised the worst. The dominating performance of the Combined scenario, for both methods used, is unsurprising. A similar issue arises with Actor 5 who described their preference for scenarios with good economic performance and job creation as a means to ensure sustainability. These stated preferences and weights are largely respected by both methods in ranking the Combined scenario, the scenario most expensive to construct but with the highest job creation and cheapest electricity price, as their most preferred scenario due to the emphasis the Actor placed on each criteria and the scenario's relative performance on them.

5 Policy implications and recommendations for 2050

The findings from the 2050 scenarios developed in this work achieve the goal of Reunion Island electrical energy self-sufficiency. What is clear from the results of the MCDA rankings is that not all scenarios are attractive to the island stakeholders, in particular the Base scenario which appears to be the least preferred option. The Combined and Optimised scenarios are potentially both attractive, but as Reunion Island has limited biomass energy resources, achieving energy self-sufficiency is mainly a result of developing renewable energy resources with the lowest greenhouse gas emissions. Reducing these emissions is therefore consistent with the development of the island's energy autonomy and favours the Combined scenario. Therefore, photovoltaic and wind energy should be developed to their maximum capacity, in addition to other non-intermittent resources such as OTEC and geothermal. These last ones, which are under development, are crucial in reaching the island's self-sufficiency goal in electricity and should be facilitated in the following years as already suggested in [10]. This leads to a diversity of technologies increasing island's resilience [84]. Further, employment on the island is a major local issue, the island's unemployment rate was 17.1% at the end of 2022 as compared to 7% in mainland France [85,86]. This need for transition scenarios to create jobs is recognized by all Actors in their weights, and indicates a wider potential attractiveness of the Combined scenario.

The stakeholders included in this evaluation provide a range of preferences, and expanding the group of stakeholders involved would increase the social representativeness, and potentially acceptance, of plans developed for the island. Recently, major construction projects were stopped by local opponents on the grounds of their environmental impacts. This highlights that stakeholder's positions should also be properly evaluated and considered when developing plans, such as potentially through a survey, to further include a wider range of perspectives.

Even given the broad aims of each of this paper's four scenarios, these results give Reunion Island's energy system planners a number of clues as to how to design the 2050 energy system. Systems that use high amounts of batteries and renewables are acceptable, given that they do not become too expensive in a social, economic, or environmental sense. Taking this result a step further, while the system must be technically possible, the precise details of how this is done are not of the greatest interest to stakeholders. What is of interest, and is clearly linked to the technologies used, are the environmental consequences, job creation, economic costs, and social impacts of the system. This means that the plans created should emphasize all these points when developed and when presented to the island's inhabitants and the relevant key stakeholders. In this study, demand management was only considered for EV charging. Other sectors may be able to contribute to demand management program. More incentive programs could lead to lower operational costs, lower biomass use and a more resilient grid [31].

6 Conclusion

This work ranks four long-term energy scenarios for Reunion Island using a MCDA approach with two methods and considering local stakeholders' perspectives. Reunion Island's electricity self-sufficiency represents a significant challenge due to the island's limited land area and high energy consumption levels. Considering a 2050 time horizon, four scenarios have been investigated to reach electrical energy autonomy. The Base scenario includes generation with a high proportion of dispatchable resources. The Intermittent scenario, on the other hand, incorporates mainly intermittent renewable resources. The Combined scenario considers all the island's energy resources at their maximum capacity. Finally, the Optimised scenario minimises the investment cost of the energy system. Eight criteria are considered to compare these scenarios covering the environmental, economic, technical and societal domains. In the social domain, a criterion is proposed to consider the impact of the technologies on society (noise, visual and land use impacts) on this geographically constrained island. No single scenario is preferred by all local stakeholders, though all preferred either the Combined or Optimised scenarios. There is, across both methods, slight preference for the Combined scenario, explained by its lower GHG emissions and a greater number of jobs created. These findings indicate that as Reunion Island begins making plans to achieve electricity autonomy by 2050, policies encouraging the development of solar and wind resources should be instituted to achieve their maximum potential. Doing so will reduce biomass use, supplies of which are limited on the island, and GHG emissions and create as many jobs as possible.

Further, development of many energy sources will boost resilience by allowing production compensation. To reduce battery and biomass use, non-intermittent sources are essential. Despite its larger social impact, geothermal energy is an excellent candidate because it is mature and may provide more jobs. If electric demand declines, new technology may not be needed. Indeed, consumption, the foundation of power network models, will determine the island's future electric autonomy.

Data availability

All data used for the research is provided in the paper.

7 CRediT author statement

Conceptualization: D.G., C.T. and A.B; Data curation: D.G., C.T., A.B. and A.F.; Formal analysis: D.G., CT., A.B. and H.P.; Funding acquisition: M.B., and H.P.; Investigation: D.G., C.T., A.B., and A.F.; Methodology: D.G. and A.B.; Supervision: H.P., B.M. and M.B.; Software: A.F.; Validation: D.G., B.M. and M.B.; Visualization: D.G., A.B. and A.F.; Roles/Writing - original draft: D.G., C.T., A.B. and A.F.; and Writing - review & editing: D.G., C.T., A.B., A.F., H.P., B.M. and M.B.

8 Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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