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Multicritery Decision: Application in the Selection of Alternatives of Generation of Electric Energy — From the Environmental Economy to the Ecological Economy

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Abstract: With the objective of selecting alternatives for electric power generation in Bolivia from the viewpoint of the Ecological Economy in substitution of the Environmental Economy that has not solved the emissions of greenhouse gases and the depletion of energy resources, was used multicriteria decision (multi-objective programming), as decision instruments to resolve conflicts between the criteria: environmental (emission of greenhouse gases expressed in CO2eq), social (generation of jobs), economic (Normalized cost of energy, LCOE) and impact (cost of impacts on the environment, health and others) of nine alternatives: Thermoelectric to Natural Gas, Nuclear, Large Hydroelectric, Small Hydroelectric, Solar Thermal, Solar Photovoltaic, Wind, Geothermal, and Biomass. This method required data criteria for each alternative, available energy resources for each technology and power demanded by the population. Set the order of priority selected of the alternatives were: Wind, 31%; Small hydroelectric, 18%, Solar thermic, 18%, Solar photovoltaic, 16%, geothermal, 15% and biomass, 2%. Concluded that it is possible to generate a new energy matrix based on renewable resources with principles of ecological economics instead.

Key words: multicriteria decision, ecological economic

1. Introduction

Without a doubt, the generation of electricity contributes in the problem of climate change, the Assembly of the United Nations (UN) in repeated resolutions has stated that climate change is a threat to sustainable development and the survival of the Nations, and required urgent and ambitious action.

In the Rio+20 Conference, (abbreviated name of the United Nations Conference on sustainable development), world leaders, along with thousands of participants from the private sector, non-governmental organizations and other groups, came together to shape the way in which can reduce poverty, promote social equity and the protection of the environment in an increasingly populated world, official talks focused on two main themes: how to build an ecological economy for development sustainable and removing people from poverty, and how to improve international coordination for sustainable development. It is an historic opportunity to define the pathways to a sustainable future, a future with more jobs, more clean energy, greater security and a decent standard of living for all [1].

Ecological economics, basically is a new economic school based on other philosophies, seeking to understand the multidimensionality of the environment, (...), it is a term opposite to environmental economics, based on the laws of the thermodynamics and large biosphere ecosystem biogeochemical cycles, emphasizes the finitude of natural resources in the environmental management policy proposals [1].

While, the environmental economy is constituted as discipline as a response of neoclassical economists to contemporary environmental issues based on the same

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basic concepts of neoclassical theory, which concentrates the analysis about shortages, and where goods are valued according to their abundance and rarity, is based on the theories of the internalization of the externalities of Pigou and Coase, both of the neoclassical school [2].

The incorporation of the environment to the market would be through the internalization of these externalities of Pigou and Coase procedure.

The energy sector plays a fundamental role in economic development. However, various controversies in implementation exist an alternative or another, for example, some support the installation of nuclear power plants by various attributes, others defend the use of hydrocarbons; others are defenders of hydroelectric plants; others alternate such as wind, solar, geothermal and biomass energy; and others reject it. The availability of energy resources should be added to these controversies.

Therefore, there is a diversity of opinion, on behalf and against the various alternatives of electric power generation, is even more problematic when all alternatives must comply with different objectives and that are conflicting with each other as indicates [3].

Therefore, the research is a set of objectives to be fulfilled by each alternative that are conflicting among them, therefore has the character of multi objective. As these multidisciplinary objectives is adopted the ecological economy instead to environmental economics. Although both economic approaches claim to deal with the useful and the management, ecological economics considers that all the biosphere and resources may be both scarce and somewhat useful [4].

Select alternatives for generating electric power to develop a new energy model in Bolivia, based on the ecological economy, using multicriteria decision theory for the minimization of conflicts between alternatives.

2. Material and Methods

Of the different criteria which have alternatives or electricity producing technologies, this study considered four: environmental (emissions of carbon dioxide, social (number of jobs), economic (LCOE: Levelized Cost of Electricity) and impacts (cost of the impacts).

Alternatives or technologies producing electricity which were considered in this study are those that could be installed in Bolivia they are: natural gas, nuclear, large hydroelectric, small hydroelectric, solar photovoltaic, thermoelectric solar thermal, geothermal and biomass.

Methods of decision multicriteria used in the study is the multiobjective programming followed by the method of the weights as a technique for generating efficient set. The information required by the method can be seen in Fig. 1.

The mathematical model for multiobjective programming consists of objective and constraint functions, as seen below:

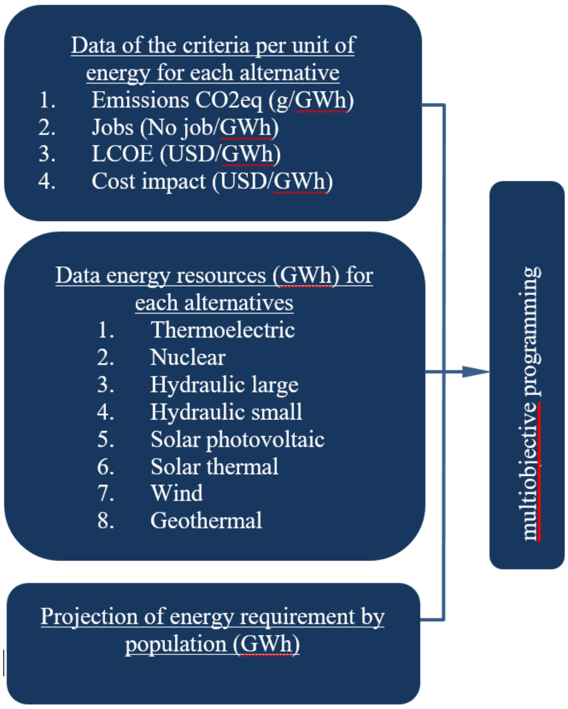

Fig. 1 Information required for the decision method.

$$OF: Min \sum_{k=1}^{4} \sum_{i=1}^{9} (a_{ki} x_i)$$

$$\sum_{k=1}^{4}\sum_{i=1}^{9}(b_{ji}x_i) \leq ER_j$$

$$x_i \geq 0$$

Where OF is objective function (can be of minimization or maximization), a_{ki} are the values of the criteria, x_i are the quantities of energy that each alternative produces, b_{ji} are the coefficients of the amounts of energy (in this case it is one), ER_j amount of energy resource that Bolivia has, it is to comply with the restrictions.

To determine the technological alternatives that are capable of producing the required energy, and that all objective functions comply with the planned, for CO_2 emissions, LCOE and cost of impacts must be minimal and for the number of jobs the objective function is to maximize.

Being that the evaluation of the objective functions reports four different results of energy production by the alternatives, denominated as ideal results, is that the weighting method is used as a way to obtain the best option.

This method consists of achieving a single weighted objective function from the sum of all the objective functions multiplied by a weighting factor (which in this case is varied to 0.7 for an objective function and 0.1 for the rest, then a combination is made, likewise, the value of 0.25 is considered for each objective function, with the values of the variables, the objective functions are calculated again, from which the best of the alternatives is chosen, followed by the mathematical model:

$$FO_p = \min \sum_{k=1}^{p} \lambda_k f_k(x)$$

$$\sum_{k=1}^{p} \lambda_k = 1$$

Where λ_k are the weighting coefficients, to give an importance to the objective functions, this value is chosen randomly. For some value of λ there will be a satisfying result.

The analysis of the multi-objective programming was carried out for different scenarios (2020, 2030, 2040 and changes in the 2040 scenario) chosen for the availability of energy resources such as natural gas, nuclear, etc.

The multi-objective programming was evaluated using the solver, which is a tool that Excel has.

Tables 1 to Table 4 show the data referring to the criteria for the alternatives, for each scenario. This data is available in Refs. [5-12].

Table 1 CO_2 emission projection (10^5 g/GWh).

Technology	2020	2030	2040	> 2040
Gas	4430	4430	4430	0
Nuclear	660	660	660	0
Hydro Large	130	130	130	65
Hydro small	130	130	130	65
Solar PV	320	320	320	320
Solar thermic	130	130	130	130
Eolic	100	100	100	100
Geotermic	380	380	380	380
Biomass	140	140	140	140

Table 2 Jobs in (Job/GWh).

Technology	2020	2030	2040	> 2040
Gas	0.464	0.512	0.512	0.512
Nuclear	0.3	0.571	0.571	0.571
Hydro Large	0,129	0.116	0.116	0.116
Hydro small	0.018	0.016	0.016	0.016
Solar PV	0.263	0.237	0.237	0.473
Solar thermic	0.07	0.063	0.063	0.127
Eolic	0.098	0.088	0.088	0.265
Geotermic	0.015	0.014	0.014	0.028
Biomass	0.062	0.055	0.055	0.055

Table 3 LCOE USD/GWh.

Technology	2020	2030	2040	> 2040
Gas	57300	57800	58300	58300
Nuclear	99100	94350	89600	89600
Hydro Large	66200	64300	62400	62400
Hydro small	66200	64300	62400	62400
Solar PV	85000	77200	69400	69400
Solar thermic	242000	223150	204300	204300
Eolic	63700	60650	57600	57600
Geotermic	46500	51950	57400	57400
Biomass	102400	96700	91000	91000

Table 4 Cost of impact USD/GWh.

Technology	2020	2030	2040	> 2040
Gas	11760	11760	11760	11760
Nuclear	10	10	10	10
Hydro Large	190	190	190	190
Hydro small	130	130	130	130
Solar PV	1970	1970	1970	1970
Solar thermic	1970	1970	1970	1970
Eolic	360	360	360	360
Geotermic	1040	1040	1040	1040
Biomass	3410	3410	3410	3410

To determine the projected energy requirement by the population, electricity consumption data was taken every month from 1996 to 2016, reported by the Ministry of Hydrocarbons and Energy [13, 14]. Consumption is expressed in series of time with characteristics of seasonality and trend, so the prognosis is prudent to analyse by the method of triple smoothing or better named method of Holt Winter multiplicative.

In order to compare the results, for 2022 the consumption is 13109.8 GWh, this value is similar to that reported by the Ministry of Hydrocarbons & Energy (2012) in its study of: Optimum projection of expansion of the national interconnected system 2012-2022. In 1996 and 2015 the electric power requirement for the Bolivian population was 2502.3 and 8882.5 GWh respectively, and by projection for the years 2020, 2030 and 2040 it was 11892.3, 17979.5 and 24066.7 GWh respectively. But in some scenarios, it was increased to 48000 GWh as a preventive projection.

The analysis of the multi-objective programming was carried out for different scenarios chosen for the availability of energy resources, these are 2020, 2030 and 2040, however, for scenarios more than scenario 2040 (+2040, + 2040-2, + 2040-3, + 2040-4, + 2040-5 and + 2040-6) are assumed by the availability of energy resources based on the ecological economy.

Energy resources are determined by different methods. Table 5 shows the energy resources available for each technology. The data is available in Refs. [15-23].

Table 5 Energy resources available for each technology in Bolivia.

Recursos energéticos	2020	2030	2040	+2040	+2040-2	+2040-3	+2040-4	+2040-5	+2040-6
Natural Gas	276362	1095	0	0	0	0	0	0	276362
Nuclear	0	1000	5000	0	0	5000	0	5000	5000
Hydro Large	48635	48635	0	0	0	0	0	14007	14007
Hydro small	14007	14007	14007	14007	14007	14007	14007	14007	14007
Solar PV	2666	6094	11426	11426	114260	11426	11426	11426	11426
Solar Thermic	2666	6094	11426	11426	114260	11426	11426	11426	11426
Eolic	15000	15000	15000	137663	137663	137663	15000	15000	15000
Geotermic	876	2628	11037,6	11037,6	11037	11037	11037	11037	11037
Biomass	1182	1182	1182	1182	1182	1182	1182	1182	1182

3. Results and Discussion

In the multicriteria decision method (multi-objective programming), data was used on the criteria of the alternatives, the energy resources available in Bolivia for each technology and the energy requirement by the population for each scenario.

As a result of the evaluation of the multi-objective programming for scenario, the production of electric energy by the alternatives appears in greater or lesser quantity for each objective function, as an example in Fig. 2 shows the generation of electric power by the alternatives for the scenario + 2040-5.

And, in Fig. 3, the results for the objective functions are shown. The values of the objective function for each scenario analysed in the study. In which the

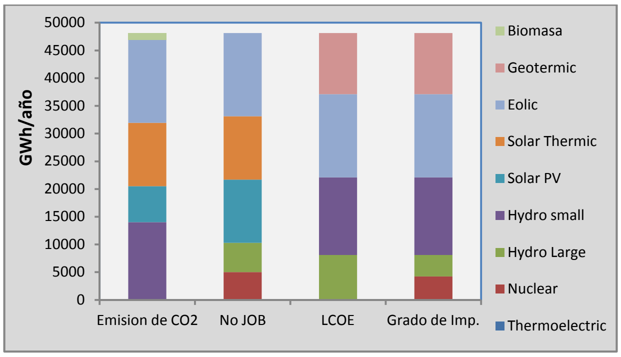

Fig. 2 Energy for the scenario + 2040-5.

eloquence of the conflicts between the objective functions can be evidenced by its multicriteria character, each objective function converges to values that fulfil the minimization or maximization.

In the same Fig. 3, for the objective function LCOE, its values remain below 60 USD/MWh, for all scenarios except for scenario + 2040-4 in which wind energy resources are reduced. For this scenario, the cost of the impacts also rises considerably to reach 827.4 USD/GWh, which is the highest value of all the scenarios, while for the other scenarios they range between 400 to 100 USD/GWh. With respect to the objective emission function of CO_2eq, also for scenario + 2040-4, it increases considerably, for the other scenarios they remain between 10 and 14 tn CO_2/GWh. It could be said that for the jobs objective function, the decrease in wind energy resources have also affected in scenario + 2040-4, in this case with the decrease in jobs.

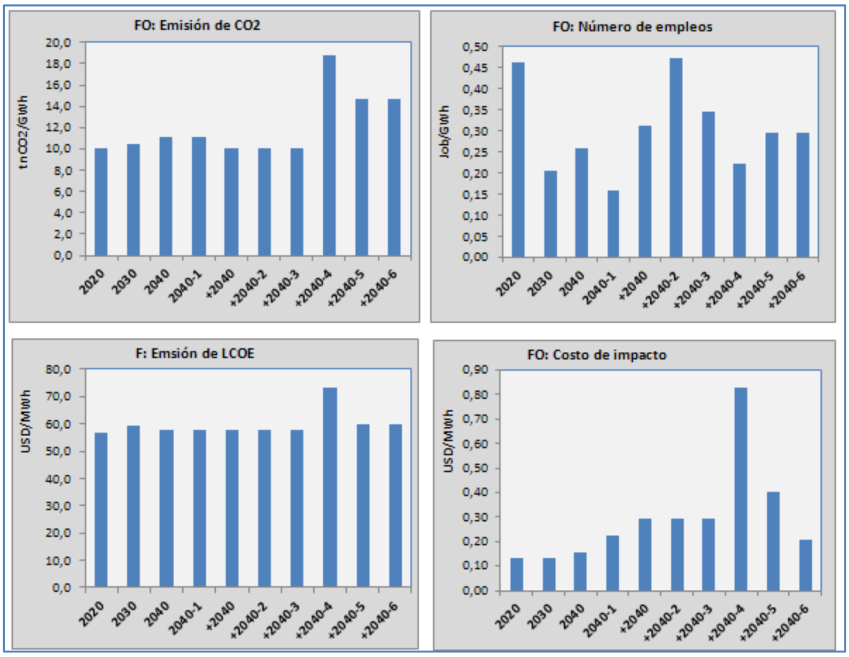

Fig. 3 Summary of values of ideal objective functions.

At first sight, it could be said that the best option is scenario + 2040-2, when for reasons of minimizing the extraction of non-renewable energy resources such as natural gas, nuclear and large hydroelectric plants based on ecological economy which privileges the finitude of these energy resources, the values of the objective functions are the most adequate, although not the best, the number of jobs are high, the LCOE also adopts adequate values. In the same way, the objective function of impacts adopts adequate costs, although not as low as other scenarios, but better than others.

The Ecological Economy also privileges the minimization of possibilities of increasing entropy, it is achieved with emissions of greenhouse gases a fossil resource such as natural gas that in the reservoir its entropy was low, but by combustion by-products (CO_2

and others) is in another state of greater entropy, both the gases emitted and the dissipated energy is impossible to return to its natural state. That in this case the gases are caused by the emissions referred to that is made throughout the life cycle of the technologies, in other words, are inevitable emissions that are generally caused to the construction of technologies, but not in their functioning. Likewise, the social economy privileges the welfare of society, the minimum impacts and number of jobs by technologies, contributes to this attribute.

So far, no point of convergence has been obtained for all the objective functions, for which the following section shows the results of multicriteria by weighting averages, as a method of approaching convergence to satisfactory results, that is to say, the possible the best, Fig. 4.

Based on Fig. 4, for the 2040 scenarios the energy requirement of 24066 Gwh is possible to generate only with the small wind and hydroelectric technologies, while considerably increasing the energy resource in the scenarios +2040-1 to +2040-3 is it is possible to produce energy only with wind, even if the requirement is double. In the scenario + 2040-6, thermoelectric, nuclear and hydroelectric power plants are involved, but the model (simulation) does not consider them. However, in scenario +2040-4, does not consider these resources, so that this scenario could be selected as the basis for a new energy matrix, where several alternative technologies participate, although the values of the objective functions are a little higher than in the other scenarios.

In Fig. 5, the values of the objective functions obtained by the averaging method are shown. Where you can see the most expected scenarios judging by the values of the corrected objective functions.

For the emission objective function, in scenarios 2020 to +2040-3, they adopt minimum emission values of CO_2eq, but increase in scenarios +2040-4 to +2040-6.

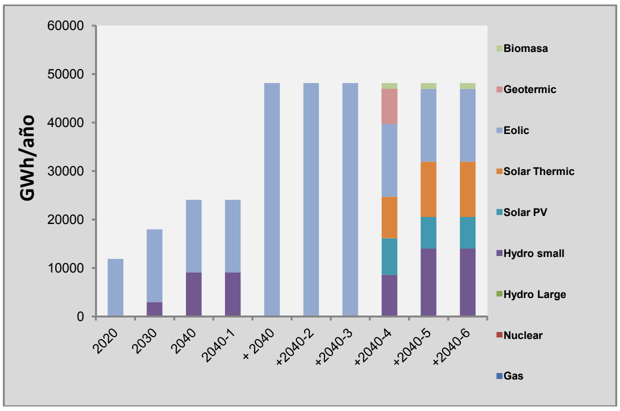

Fig. 4 Tecnologías para la función objetivo de ponderación.

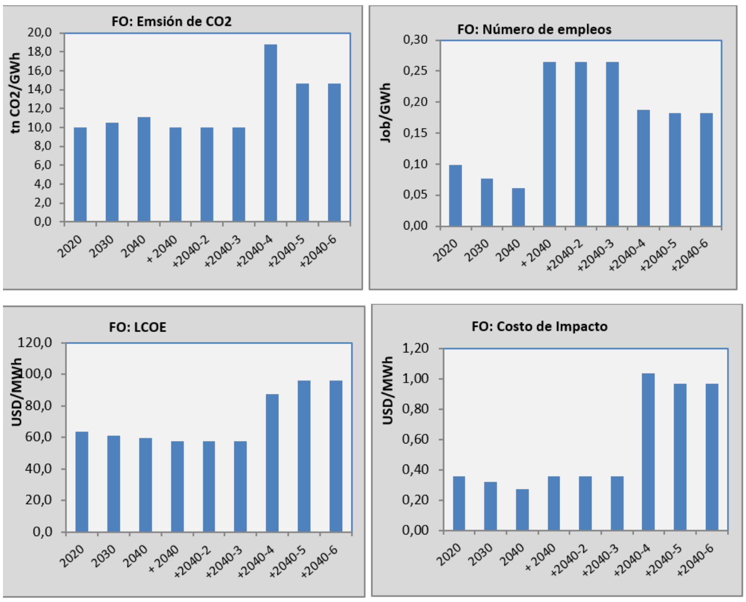

Fig. 5 Weighted objective functions.

Whereas that, the employment objective function, the first three scenarios adopt low employment values, but its value increases considerably in the scenarios of +2040, +2040-2 and +2040-3, in these scenarios the natural gas energy resources do not participate, large hydroelectric or nuclear, only in the scenario +2040-3 nuclear participation. In scenarios +2040-4, +2040-5 and +2040-6 when the natural gas, large hydroelectric and nuclear power resources are again taken into account, the number of jobs decreases, although not in the values of the first scenarios.

With respect to the LCOE objective function, the last three scenarios adopt high values compared to the other scenarios, coinciding with the participation of the aforementioned energy resources (natural gas, large hydroelectric and nuclear).

The same tendency occurs with the objective function cost of impacts that with the objective function LCOE.

Therefore, in the first three and three last scenarios, all energy resources participate, precisely in these scenarios where values of inconvenient functions are observed, but when these energy resources do not participate, for example, in the three intermediate scenarios (+2040 +1, + 2040-2 and + 2040-3) the objective functions adopt convenient values.

4. Conclusion

It could be concluded that scenarios + 2040-1 and + 2040-2 are the most appropriate scenarios, although with the weighting method the wind energy resource is sufficient to produce the required energy; however, seeing in the multiobjective programming the ideal values of the objective functions of these scenarios (when no energy resources of natural gas, hydroelectric and nuclear power are involved) are similar and adequate, in addition the participating technologies are varied, the wind in higher percentage, followed by solar photovoltaic, geothermal and small hydroelectric.

Even though the values of the objective functions are relatively adequate in scenario + 2040-3, it is not taken into account since the nuclear energy resource participates, since their participation contributes to the worsening of the objective functions, in addition, their participation is in low quantity.

However, despite the fact that the objective functions for scenario + 2040-4 are although weakly adverse compared to the other scenarios, but all technologies with renewable energy participate. For example, emissions are considerably low compared to thermoelectric emissions, in terms of jobs and LCOE they maintain similar values, but the cost of impacts is relatively high. Both in the case of emissions and in the impact, controls could be improved, especially in the use of biomass, and adopt scenario + 2040-4 as the most viable alternative to initiate a change in the energy matrix under the principles of the Economy. Ecological.

Therefore, scenario + 2040-4, although the objective functions are slightly unfavourable, it can be seen that all the technologies that work with renewable energies participate, so it is taken as a feasible alternative taken from the point of view of the Optimum Pareto (represents a point of balance where you cannot give or ask without affecting the economic system).

In the sense that the alternatives that would be part of a new energy matrix, are: Wind, 31%; Small hydro, 18%; Solar thermal, 18%, Solar photovoltaic, 16%, Geothermal, 15% and Biomass, 2%. That is, these alternatives are sufficient to produce the amount of electricity required by the population, using energy resources available in Bolivia.

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