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# Multiple Criteria Decision-Making as an Operational Conceptualization of Energy Sustainability

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**Abstract:** There is a broad international consensus about the urgency of promoting a strong change towards energy models that are less dependent on non-renewable energy sources, more equitable, and truly environmentally friendly. In order to achieve this goal, we need to define the problem so that it can be operationally and comprehensively addressed. This paper presents a proposal of a framework for the analysis of the sustainability of energy models based on multiple criteria theory, which we consider comprehensive and operational enough. Its application to a real energy model, the Spanish one, shows that the framework is able to address most of the elements both of weak and strong sustainability and find a reasonable compromise within the limits of the problem.

**Keywords:** energy sustainability; weak sustainability; strong sustainability; sustainability frameworks

## 1. Introduction

Making our way of life sustainable for our growing world population is a challenge unparalleled in human history. Like any great challenge, it is necessary to carefully design the plan or roadmap that will lead us to its achievement. However, any plan worth its name must be based on a deep understanding of the problem it seeks to address. This is where this paper intends to make a contribution. Specifically, we intend to offer a rereading of the challenge of sustainability itself, especially with regard to the energy dimension, and to offer a framework that is operational, i.e., that can be applied with reliability to the different subsystems that make up this problem. To this end, after an introduction in which we will unravel the ins and outs of the challenge of sustainable development, we will present a proposal for an operational conceptual framework based on the multi-criteria theory.

### 1.1. Energy and the Problem of Sustainable Development

In the middle of the 20th century, we saw our planet from space for the first time. Historians may eventually find that this vision had a greater impact on thought than did the Copernican revolution of the 16th century, which upset the human self-image by revealing that the Earth is not the centre of the universe. From space, we see a small and fragile ball dominated not by human activity and edifice but by a pattern of clouds, oceans, greenery, and soils. Humanity's inability to fit its activities into that pattern is changing planetary systems, fundamentally. Many such changes are accompanied by life-threatening hazards. This new reality, from which there is no escape, must be recognized - and managed.

The text above is contained in the first chapter of the United Nations report "Our Common Future", better known as the Brundtland Report [1], which contributed in an extraordinary way to the popularization of the concept of Sustainable Development (SD). The report had two fundamental objectives: (1) to give as objective a vision as possible of the unsustainable path on which human development was moving and (2) to emphasize the need for an international effort capable of reversing this situation.

The Brundtland report was a milestone. It opened the eyes of the international community to a problem that, if left unaddressed, could have dramatic consequences for

the planet and our way of life. Today, 34 years later, we are even more aware of the problem and its causes.

According to World Bank statistics, the world population has grown from 3.01 billion people in 1960 to 7.67 billion in 2019, i.e., there has been a growth of more than 150% in 60 years. At the same time, the increase in world GDP (in constant 2010 dollars) went from $11.35 trillions in 1960 to $84.85 trillions in 2019. In short, this is a scenario of unprecedented growth in human history. The question to be asked, and which the Brundtland Report already anticipated, is whether this growth is taking place in a sustainable manner, i.e., respecting the critical limits and assuring equity in the distribution of welfare for current and future generations. Unfortunately, there are many signs indicating that growth patterns are not actually being sustainable. One of the most clear examples is the results of the successive IPCC reports on global warming. If greenhouse gas emissions are not curbed, by the end of the 21st century we could be facing a scenario of global temperature rise of more than 3 degrees Celsius, which could be catastrophic for many ecosystems and societies. On the equity side as well, the signs are worrying. Taking as a reference the world's leading economy, that of the United States, it may be seen that the Gini index, which measures the deviation of the balance in the distribution of income, grew, according to the OECD, from 0.345 in 1979 to 0.414 in 2018. That is to say, despite the fact that US GDP in this interval almost doubled, inequality in the distribution of GDP still increased.

It is interesting to note that the variables mentioned above to exemplify the drivers of the sustainable or unsustainable evolution of our society encompass three very different spheres, i.e., economic, social, or environmental. That is precisely the classical approach to sustainability, i.e., the triple bottom line [2]. According to it, achieving sustainability requires that we pay adequate attention to each of the three dimensions.

Now, getting into the sector that mainly concerns us, that of energy sustainability, it is worth analyzing how energy interacts with each of these three areas.

According to economist Schumacher: "energy is not just another good, but the precondition of all goods, a basic factor such as air, water and land" [3]. Energy is something that every human being on the planet uses directly and indirectly on a daily basis. It is the raw material for all our economic activity: the total global primary energy supply (TES), according to the IEA, went from 6098 Mtoe in 1973 to 14,282 EJ in 2018. In other words, it has more than doubled in the last 45 years. These data suggest that the impressive economic growth of recent times has been based, to a large extent, on an ever-increasing energy consumption. This fact in itself may not be a problem as long as the primary energy sources used are sustainable, but unfortunately this is not the case. Taking 2018 as a reference year, the dependence on non-renewable sources is enormous: 24.5% of coal, 46.2% of oil, and 16% of natural gas.

In total, 87.7% of the world's TES in 2018 was covered by fossil fuels. In addition, despite improvements in technologies, emissions due to this pattern of energy production have not stopped growing. If we focus on greenhouse gas emissions linked to fossil fuel use alone, these have risen from 15,459 million tonnes of $CO_2$ in 1973 to 33,513 million tonnes in 2018. On this point, the IPCC has been particularly clear: if we want to limit the increase in the global temperature of the planet to 2 degrees by the end of the century (450 ppm CO2eq), it is necessary to reduce emissions by between 40% and 70% by 2050, and practically 100% by 2100, taking 2010 as the reference (IPCC, 2014) (all evidence suggests that these estimates will be greatly constrained in the IPCC's Sixth Assessment Report to be presented in 2022.). Of concern are also the harmful health effects of other fossil-fuel-related emissions: NOx, $SO_2$, and PM2.5, an issue that has been repeatedly brought by the WHO (WHO, 2013).

In light of these data, the centrality of energy in the environmental and economic dimensions of SD is evident, but it also has a direct influence on the social pole. Linked to the patterns of energy production and consumption, various social problems arise, such as ethical issues related to universal supply at affordable prices (a fact that in industrialized countries is beginning to be recognized with the term "energy poverty" or "fuel poverty")

or geopolitical problems derived from the concentration of primary resources in certain areas of the planet.

It therefore seems clear that there is also a problem of unsustainability in energy models. What needs to be defined now is where we need to go, that is, what requirements an energy model must meet so that it can be called sustainable.

### 1.2. How to Define a Sustainable Energy Model

The first step in resolving any problem, whatever its nature, is to define it. However, as Pezzey points out [4], in the case of SD, this exercise has turned out to be a pipe dream. Many definitions have been presented to date, and many conceptualizations have emerged from them. Although each one has its own pros and cons, the capital-based proposal is very promising when trying to operationalize sustainability issues in general, and sustainability of energy systems in particular. Neumayer [5] suggested that an operational conceptualization of the problem of SD should be based on the protection of the various types of capitals that are the means to satisfy all human needs. Capital is understood as any accumulation of resources from which we derive welfare. From economic capital, we produce monetary rents; from human capital or accumulated knowledge, we are able to solve intellectual, engineering, or scientific problems; from social capital, institutions that allow us to relate to others, we receive support and relationships; and from natural capital, we obtain natural resources, recreation, or support of life. From this point of view, the sustainability of our societies would be guaranteed if a non-decreasing and equitably distributed stock of capital in space and time were to be ensured, thus enabling human needs to be met in a sustainable manner.

Although this capital-based conceptualization represents a significant step forward in the operationalization of the problem of SD, it is not without its problems. The main one has to do with the role that natural capital plays within the model. This is precisely the issue around which the two main schools of thought on Sustainable Development, i.e., weak and strong paradigms, collide.

The Weak Sustainability (WS) paradigm was founded in the 1970s by extending the neoclassical theory of economic growth to include non-renewable natural resources as a factor of production. The key issue being investigated was whether economic growth was sustainable in perpetuity, in other words, whether a non-decreasing level of well-being over time in a context of finite resources was possible.

The concept of Strong Sustainability (SS) is rooted on Georgescu-Roegen and Daly's works [6,7]. A clear underlying idea was present in those studies: there is an urgent need to define absolute limits to activity that safeguard the conditions that make life on Earth possible, or in other words, it is urgent to define a critical natural capital.

The difference between the two paradigms is essentially the possibility or not of substitutability between capitals and, in particular, the treatment of natural capital. For WS, natural capital is no different from other capital and can be substituted without limitation. On the contrary, proponents of the SS paradigm argue that natural capital is by no means substitutable with other capital.

Both approaches suffer from particular constraints that make them incapable of covering all aspects of energy sustainability on their own. That is why, in our view, it was necessary to propose an integrated approach that includes both contributions.

That is exactly the gap that Linares tried to cover. With the inspiration coming from Neumayer [8] and Pearce [9], Linares [10] presented his framework. He proposed a conceptualization of sustainability based on the four main capitals, namely economic, social, human, and natural, that must be complemented by the equity aspect. All of this must also be subject to critical limits in those criteria, where the precautionary principle

persuades us to remain within the safety zone. This framework is summarized in the following formulation:

$$\dot{K} = \frac{\partial k_e}{\partial t} \oplus \frac{\partial k_n}{\partial t} \oplus \frac{\partial k_s}{\partial t} \oplus \frac{\partial k_h}{\partial t} \geq 0$$
$$s.t.$$
$$k_i \leq CL_i, \forall i \qquad (1)$$

where $\dot{K}$ represents the variation of the aggregated capitals over time, $k_i$ stands for each type of capital, and $CL_i$ stands for critical limits.

It may be observed that the proposal brings together the two sustainability schools, WS and SS, in a very specific way. On the one hand, the function to be optimized is an adaptation of Hartwick's rule [11], where it is simply demanded as a condition of sustainability that the aggregate of capital is non-decreasing over time. On the other hand, this framework takes a step forward by incorporating critical limits for all capitals, which is what actually sets the minimum conditions for sustainability according to SS. These critical limits may be understood as minimum amounts of aggregated capital that must be preserved, but also as minimum amounts accessible to every individual and which enable that individual to enjoy a good life.

At this point, we are already in a position to answer the central question at stake: what requirements does an energy model have to meet in order to be sustainable? Any possible response to that question requires starting from a certain conceptualization of SD, and it is precisely here that the previous introduction, which has led us to Neumayer's capital-based proposal, and then to Linares' proposal that integrates WS and SS, makes sense.

Thus, we consider that the sustainable energy model to pursue is one that (1) makes possible a non-decreasing level of well-being that is produced by the four types of capital, or in other words, one that assures that the stock of capital increases or at least does not decrease; (2) contributes to inter and intra-generational equity; and (3) respects the critical limits.

The first and the third conditions are already included in Linares' proposal presented above, but the integration of the second is still pending. That will be one of the objectives of this work. The second will be the formalization of the entire energy sustainability framework. In order to get there, a review of the state of the art of multicriteria sustainability frameworks was conducted.

## 2. MCDM as a Framework for Operationalizing Sustainability

Bibliographical references to this topic of frameworks for sustainability are extremely extensive and diverse. In this particular investigation, the field of search has been narrowed to a specific family of proposals, namely multi-criteria methods. This choice was fundamentally due to the fact that these methodologies fulfilled the main requirement sought, that is, that they allowed the different dimensions of sustainability, and their corresponding capitals, to be integrated within the same operational and scalable framework. In addition, multi-criteria techniques make it possible to incorporate human preferences in the design of sustainability policies. We will return to this point later.

Moreover, these methodologies have shown themselves to be good candidates to deal with the apparent contradiction between WS and SS highlighted above. Multi-criteria methods are techniques that seek to place different criteria on an equal footing in which each one can adequately affect the decision to make. These methodologies are therefore perfectly compatible with the capital substitution proposal by WS. In fact, they have been widely used to quantify and incorporate economic externalities into decision-making processes. In addition, multi-criteria techniques also allow for the incorporation of criteria from the SS into SD decision-making, as will be shown below.

Multi-Criteria Decision-Making (MCDM) or Multi-Criteria Decision Analysis (MCDA) encompass a set of different existing techniques suitable for addressing problems featuring

high uncertainty, conflicting objectives, different forms of data and information, and multiple interests and perspectives [12–14].

Thus, these techniques are suitable when dealing with a multiple criteria decision problem. When there is only one criterion, a technological problem is being faced in which no election is to be done but rather just find the optimal solution. When there are indeed several criteria, the decision becomes a decision problem, and that implies a real problem of choice.

The general formulation of an MCDM problem is as follows:

$$Opt \quad z = (z_1(x), z_2(x), \ldots, z_n(x)) \quad x \epsilon F \tag{2}$$

where $z$ is the vector of $n$ criteria functions (objective functions), $x$ is the decision variable, and $F$ is the feasible set.

MCDM encompasses different techniques. They can be classified according to the space of solutions, i.e., continuous or discrete. Within the former, the most commonly used methods are: (1) multi-objective programming (MOP); (2) compromise programming (CP); and (3) goal programming (GP). The first two are considered optimization problems, while the third belongs to the so-called "satisficing problems".

Besides, in the discrete side, the most popular techniques are (1) the theory of multi-attribute utility (MAUT), (2) the analytical hierarchical process (AHP), and (3) the outranking methods, such as the Electre or Promethee.

*MCDM Applications to Sustainability*

This brief review was divided into two parts. The first concerns the use of the multi-criteria techniques as a general framework for addressing the challenge of SD in all its complexity. The second deals with the use of multi-criteria proposals to support decision-making specifically in the energy sector.

In relation to the first one, Munda's work stands out (e.g., [15]). According to him, MCDM (or SMCDM, with the "S" standing for "Social") provides a powerful framework for the implementation of the incommensurability principle, namely "the absence of a common unit of measurement across plural values since it meets several goals at the same time".

It is worth noting that this issue of incommensurability is closely linked with the classic disputation between weak and strong comparability [16] or [17]. In this regard, Martínez-Alier's position stands out. He rejects the reductionist economic proposals, i.e., reducing all the criteria exclusively to monetary variables, that, according to him, fail from their very conception of the problem.

A very recent state of the art on a different application of Munda's proposal has been developed by Etxano et al. [18].

Another proposal that has analyzed the convenience of using multi-criteria techniques applied to sustainable development is Boggia's [19], who developed a methodological approach based on multi-criteria analysis aimed at ranking areas (municipalities) in order to understand the specific technical and/or financial support that they needed to develop sustainable growth. He applied it to a case study in different areas of an Italian region. This is a very interesting contribution to the analysis of sustainability applied to territories, not so much to specific systems or sectors such as energy.

Besides, Cinelli's [20] analyzed the performance of five MCDA methods related to ten crucial criteria, among which are a life cycle perspective, thresholds and uncertainty management, software support, and ease of use. The work of Cinelli and colleagues provides a very useful overview to understand the strengths and weaknesses of the different multi-criteria techniques for sustainability analysis, although it does not explicitly address the distributional aspect. This is a very extensive work that demonstrates the good health of multi-criteria methodologies applied to interdisciplinary studies such as sustainability. It also shows the need of deepening in the proper integration of the weak and strong perspectives of sustainability.

Beyond the academia, international institutions have also promoted the use of MCDM for SD. The United Nations Framework Convention on Climate Change (UNFCCC) includes them as one of the most important tools in assessing impacts, vulnerability, and capacity to adapt to climate change. The Tyndall Centre report in 2003 [21] shows another good example of a framework proposal for energy sustainability analysis based on these techniques.

In addition to the above, there are a huge number of articles and technical reports that present MCDM sustainability analyses focused on specific sectors, technologies, or areas. Among them, many have to do with energy systems.

Pohekar in 2004 [22] reviewed more than 90 published papers in order to analyze the applicability of various MCDM methods to energy sustainability, i.e., weighted averages, priority setting, outranking, fuzzy principles, and their combinations. The 90 articles were classified according to their application area, the most popular being renewable energy planning followed by energy resource allocation. Regarding the techniques, AHP is the most used followed by outranking techniques: Promethee and Electre.

In 2009, Wang et al. published another state-of-the-art review of MCDM applied to energy systems [23]. In it, they reviewed the corresponding methods in different stages of MCDM, i.e., (1) criteria selection, (2) criteria weighting, (3) evaluation, and (4) final aggregation. The criteria are summarized from technical, economic, environmental, and social aspects. In this regard, investment cost was the most used criteria followed closely by $CO_2$ emissions. The weighting methods were classified into three categories, namely, subjective weighting, objective weighting, and combination weighting methods. Here, equal criteria weights were found to be the most popular ones. Eventually, several methods based on weighted sum, priority setting, outranking, fuzzy set methodology, and their combinations applied to energy decision-making were analyzed. Among those, AHP was the most popular.

More recently, Strantzali and Aravossis [24] developed another review focused on Decision Support Systems applied to renewable energy. They analyzed 183 studies and classified them according to the year of publication, method used, energy type, application area, criteria, and geographic distribution. The methods that were found to be the most popular were those based on AHP techniques.

In 2017, Kumar et al. [25] summarized the essential aspects of MCDM techniques applied to energy issues and outlined various performance indicators. According to the authors, no single MCDM model can be ranked as best or worst; each method has its own strength and weakness depending upon its application on all of the consequences and objectives of planning. They also highlight the need for a process of hierarchy so that sustainable energy planning can be evaluated not only considering a single scenario based on multiple criteria but also considering multiple scenarios based on multiple criteria. This work by Kumar et al. is particularly illuminating in terms of the need to transcend substantive rationality when addressing sustainability issues.

Mardani et al. [26] selected and reviewed 196 papers, published from 1995 to 2015, in 72 journals related to energy management. They were categorized into 13 different fields: environmental impact assessment, waste management, sustainability assessment, renewable energy, energy sustainability, land management, green management topics, water resources management, climate change, strategic environmental assessment, construction and environmental management, and other energy management areas. Furthermore, papers were categorized based on the authors, publication year, nationality of authors, region, technique and application, number of criteria, research purpose, gap and contribution, solution and modeling, and results and findings. Hybrid MCDM and fuzzy MCDM in the integrated methods were ranked as the first methods in use, and environmental impact assessment was ranked as the first area in which decision-making approaches were applied.

In addition to the above-mentioned references of state-of-the-art reviews on MCDM applied to energy sustainability, other recent articles applying MCDM techniques to specific sectors related to sustainability are: management [27,28], renewable energy [29–33],

industrial processes [34,35], economic policy [36], electricity production [37], biofuel production [38,39], big data and cloud computing [40–44], building design [45], electric vehicles [46], business and sustainability [47,48], hydrogen industry [49], Circular Economy [50], local, regional and national government [51–53], energy transition [54–56], infrastructures [57], development [58], and forest management [59].

This brief overview of MCDM applications to the SD study in general, and to energy sustainability in particular, is concluded here by analyzing its pros and cons. To the credit of these proposals, their theoretical solidity and broad development should be highlighted. These consolidated methodologies have been widely used in recent decades as tools to aid decision-making in many areas.

On the debit side, some critics of the MCDM point to one of its main features as its main weakness, namely that it has a subjective component. However, this is precisely why it is, in our opinion, more realistic than the classic reductionist decision framework. It helps to formalize complex decision problems and to make more coherent decisions.

Finally, with regard to its capacity to adapt to a concrete sustainability issue or sector, i.e., an operational framework that would be compatible with a capital-based definition of sustainability and capable also of integrating the two main schools, SS and WS, Linares' work presented above shows that the answer is positive once again. Interpreting the different capitals as criteria in an MCDM framework is a very straightforward step. It is therefore clear from this literature review that MCDM is a good method to try to operationalize energy sustainability based on a capital-based (Neumayer and Linares') conceptualization of sustainability.

## 3. Proposal

A multicriteria framework based on Linares is therefore being proposed that defines sustainability in the form of an operational optimization problem where the objective function to be optimized is dependent on capitals that are represented by several criteria, subject to a set of critical limits that can be applied not only to natural capital, but to any type of capital. This framework is totally compatible with a capital-based extended approach to sustainability that defines being sustainable as being able to create value while not exceeding the resilient limits of the planet and the society.

Measuring capitals themselves is a complex task. Therefore, it was decided to represent them using indicators (proxies) that may measure their evolution. Moreover, since building a dynamic framework would be excessively complex if we still want to keep the level of detail required for the energy system, the original Linares proposal was substituted by a static one that measures welfare in specific points in time.

Therefore, Equation (1) becomes:

$$OptK = f(k_e, k_n, k_s, k_h)$$
$$s.t.$$
$$k_i \leq CL_i, \forall i \tag{3}$$

This optimization is not directly a maximization or a minimization. It will depend on the indicators chosen to represent each capital. For example, it will be clear that from an economic capital point of view, cost minimization will be a desirable objective. However, equally desirable will be the maximization of jobs.

It is also important to note that the objective function in Equation (1) is defined neither as a sum of capitals nor as an aggregation of capitals. It merely highlights the dependency of this function to be optimized on the capitals. This way, special care is being taken with this crucial issue of aggregation as discussed above.

Next, the objective function can take different forms. Once of them is the following formulation based on multi-criteria techniques, specifically Compromise Programming.

$$\min L_p = \left[ \sum_{i=1}^{n} [w_i \frac{k_i - k_i^*}{k_{i*} - k_i^*}]^p \right]^{1/p}$$

$$s.t.$$
$$k_i \leq CL_i, \forall i \tag{4}$$

where $w_i$ represents the weight assigned to each capital $k_i$, $p$ stands for the distance to be minimized (from 0 to $\infty$), and $k_i^*$ and $k_{i*}$ represent the ideal and anti-ideal (nadir) values for each capital, respectively.

It is interesting to note that the WS side of the proposed framework presented here is in line with that proposed by Hediger [60]. Not surprisingly, the multi-criteria framework based on Compromise Programming has a direct interpretation as a function of social utility [61].

Another desirable objective for this operational framework for energy sustainability analysis is that it is capable of considering equity aspects. Thus, we proceeded to extend the previous formulation as follows:

$$\min L_p = \left[ \sum_{j=1}^{m} \sum_{i=1}^{n} [w_{ij} \frac{k_{ij} - k_{ij}^*}{k_{ij*} - k_{ij}^*}]^p \right]^{1/p}$$

$$s.t.$$
$$k_{ij} \leq CL_{ij}, \forall i, j \tag{5}$$

It can be observed that a disaggregation of the capitals according to the sub-index $j$ has been added. This sub-index might represent different population subgroups and how they participate in the different capitals. For example, for economic capital, these might be translated into income deciles. Thus, when imposing critical limits, this approach would make it possible to consider certain vulnerable groups that should be subject to specific boundaries appropriate to their vulnerable situation.

Additionally, it is also important to stress that the proposed framework responds to Martínez-Alier and Munda's suggestion of using frameworks in which the compensability is not rejected, but simply limited. (By compensability, we mean the possibility of one capital assuming the role of another. That is to say, it is a similar concept to the substitutability already mentioned above.)

Therefore, an operational capital-based framework for sustainability has been presented, but the extent to which it is scalable remains to be shown. This is a point at which the framework draws directly from the complex inspiration present in proposals such as VSM [62]. If we understand the eco-social environment in which human activity takes place as a viable system, we should define this system using a framework that is self-replicating at various scales; so is it with the proposed optimization framework.

Where this question of scaling up a particular system, such as the energy system, to the global socio-environmental system becomes especially important is when we define the critical limits. The particular limits that are defined and applied to a particular case study will have to be fully consistent with the global limits. This will mean that, in some cases, a certain a priori distribution of efforts between sectors will have to be assumed. A good example of this is $CO_2$ emissions. If we want to define an emissions limit for the energy sector compatible with the global effort to decarbonize the economy, we will have to make an assumption of distribution of $CO_2$ reduction efforts in the other sectors. Since it is defined as an optimization of well-being subject to critical limits, this framework is applicable from the highest possible level, i.e., the challenge of SD on a global scale, to the contribution of a particular sector, such as energy, to this challenge. Of course, in each case,

the indicators and constraints will have to be carefully selected, but the formal structure of the framework would be identical.

Finally, it is important to emphasize the importance of the choice of weights $w_{i,j}$. This will be the way through which human preferences can be incorporated into the framework. To obtain them, techniques such as AHP based on standardized stakeholder surveys [61] or Munda's SMCDM maninly based on NAIADE techniques [18] can be very useful.

## 4. Case Example

In this section, we present a simple example of application of the proposed framework to a real case. The objective here is not to go into the specific details of such application but to illustrate the ability of the proposed conceptual framework to be applied to real problems. For more details on the case study, the reader is referred to [63].

The case study we present is the analysis of the sustainability of the energy system in Spain to 2030. It consists of an application and resolution of the model described in Equation (5) to the Spanish energy system, which was carried out in several stages.

The first step consists of defining the decision tree that includes all the criteria to be considered ($k_{ij}$). In this case, Figure 1 shows the selected criteria as well as the type of capital they represent.
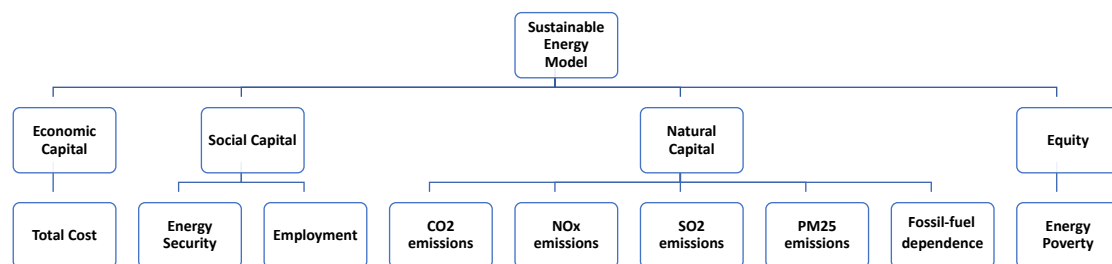


**Figure 1.** Multi-criteria tree.

Inspired by an AHP methodology (e.g., [64]), three levels were established: the upper one corresponds to the ultimate objective to be achieved, namely, a sustainable energy system; the middle one corresponds to the different capitals involved; finally, the lower one includes the different indicators identified as proper representatives of the different capitals.

Thus, it can be observed that in the third level of indicators, one was chosen for economic capital, i.e., the total cost of the system; two for social and human capital, i.e., energy security and employment; five for natural capital, i.e., emissions of $CO_2$, PM2.5, $SO_2$, $NO_x$, and fossil-fuel dependence; and finally, one indicator of energy poverty was chosen to represent equity concerns. It is important to bear in mind that we were not looking for an exhaustive description of the case but an illustration of the type of indicators to be taken into account in order to adequately represent each capital in the specific case study chosen.

It is also important to notice that this time equity was incorporated into the level of capital as one of them. This was done in order to emphasize that in this particular case, equity will have its own indicator (energy poverty). It is an indicator that comes from the breakdown of economic capital into two: vulnerable and non-vulnerable households, and seeks to optimize the latter in a particularized way, in coherence with what was proposed in the general framework. However, it should not be forgotten that in a complete development of the framework, equity should be considered in each capital.

The second step consisted in obtaining the weights ($w_{ij}$) to be applied to the multi-criteria objective function to be optimized. As discussed above, the participatory process for obtaining stakeholders' preferences is a key step in many of the multi-criteria techniques. In the case of this application, firstly, following AHP, stakeholders were asked to express the relative importance they give to each criterion by comparing them in pairs. This was

done through ad hoc online questionnaires in which they could express themselves in terms such as: criterion A is moderately more important than criterion B, or criterion B is extremely more important than criterion C. These expressions were then translated into numbers, using a scale designed by Saaty [61]. Thus, the relative preferences of each hierarchical level were obtained.

Finally, multiplying the aggregate weights according to these different hierarchical levels by those relative weights representing the relative importance of each group, the definitive weights for each criterion as a result of the AHP process were obtained.

The third step consisted of obtaining the payoff matrix, and from it, the minimum and maximum values ($k_{ij*}$ and $k_{ij}^*$) necessary for the application of the compromise programming following Equation (5).

Table 1 shows the results obtained for this case study. It may be observed that there is no single solution that optimizes all criteria, but rather there is a significant degree of conflict among them, in particular between cost, jobs, and emissions. In the matrix, the optimal values for each criteria are marked in blue whereas the anti-ideal values are marked in red.

**Table 1.** Payoff matrix 2030.

| Criteria | COST [G€] | PE [G€] | CO$_2$ [Mton] | DEP [p.u.] | NOX [Mton] | SO$_2$ [kton] | PM2.5 [kton] | SEC [G€] | JOB [Mjobs] |
|---|---|---|---|---|---|---|---|---|---|
| **COST** | **120.76** | 2.07 | 163.82 | 0.73 | **0.88** | 9.314 | **130.050** | 2.62 | **1.20** |
| **PE** | 177.44 | **1.62** | 137.10 | 0.81 | 0.44 | **53.45** | 80.07 | **3.23** | 1.52 |
| **CO$_2$** | 222.91 | 2.98 | **5.39** | 0.38 | 0.11 | 4.54 | **130.050** | 2.01 | 2.33 |
| **DEP** | 184.61 | 3.41 | 38.83 | **0.22** | 0.19 | 2.41 | **130.050** | 1.64 | 1.83 |
| **NOX** | 235.56 | 3.15 | **230** | **0.93** | **0.01** | 2.74 | 1.13 | 3.23 | 2.25 |
| **SO2** | 223.10 | 3.18 | 71.28 | 0.52 | 0.30 | **0.020** | **130.050** | 2.02 | 2.30 |
| **PM2.5** | 209.19 | 3.16 | **230** | 0.92 | 0.08 | 0.62 | **0.017** | 3.21 | 1.87 |
| **SEC** | 179.48 | 2.87 | 33.24 | 0.37 | 0.15 | 1.90 | 89.44 | **0.84** | 1.90 |
| **JOB** | **329.42** | **4.89** | 157.79 | 0.75 | 0.31 | 49.06 | **130.050** | 3.42 | **4.41** |

With all the above, we would now be in a position to solve the optimization problem.

Figure 2 shows an example of the resolution by means of a spider web graph. It shows the result of the optimization by varying the type of norm used (parameter p in (5)). Each axis of the diagram shows how far each criterion is from the optimal value, located in the center of the diagram itself. Thus, it can be seen that the most efficient result (smaller area) is obtained using $p = 1$, while using the $p = \infty$ alternative, being less efficient, manages to improve the result of the worst indicator, thus becoming a mini-max or Rawlsian approach.
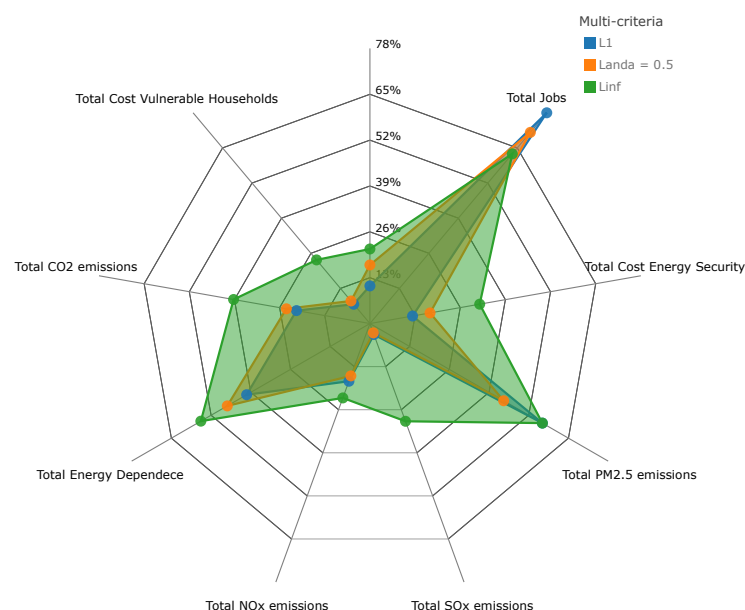


**Figure 2.** Result of the CP optimization. Case study.

Our case study shows how the more sustainable energy model is obtained by finding a balanced compromise among the different criteria so that the overall welfare derived from different capitals is maximized while subject to the limits in emissions, e.g., $CO_2$, PM2.5, $SO_2$, and NOx, and ensuring a just distribution.

## 5. Discussion

The challenge of the SD, as we understand it today, is a roadmap for the success of humanity. It encompasses not only respect for the environment, the guarantor of our survival, but also the achievement of well-being both for our generation (without exclusion) and for those to come. This major challenge has many dimensions: temporal, geographical, economic, ecological, social, and sectoral. All of them, despite having their own identity, are part of a complex web we call global SD challenge.

This paper tried to contribute to this immense goal by proposing a framework that might eventually be used to understand the extent to which our energy systems were adding to or subtracting from the global challenge of the SD. There are three conditions, in our opinion, that would have to be required of an energy system in order for it to be called sustainable, namely, (1) that it should be compatible with the global challenge of guaranteeing a human's welfare that does not diminish in time; (2) that it should respect the critical limits where and when they exist; and (3) that it should guarantee that these capitals are distributed in an equitable way. In this way, the framework to be presented would have to be able to identify to what extent an energy system was complying with these requirements. Eventually, this framework was decided to be conceptualized using a multi-criteria approach.

At first, inspired by Linares' proposal, a generalized formulation was proposed in the form of a static optimization of a specific welfare function based on capital. It was done using a compromise programming formulation, so that the framework was transformed into an optimization problem where the objective function to be minimized was the distance to an ideal multidimensional point, where each dimension represented a capital.

Then, the equity dimension was integrated into the framework by disaggregating the variables that represented each capital according to a new level that would represent the diverse distribution of capitals. This was applied not only to the objective function, but also to the critical limits. In this way, the framework would eventually allow forcing a particular distribution of some particular capital that was identified as critical.

Finally, by way of illustration, an example of the application of the conceptual framework to a real problem, namely, the energy model in Spain in 2030, has been described.

At the end of this tour, the feeling is that more questions than answers have been given. However, we do not consider this a failure, but quite the contrary. It is rather a meta-manifestation of the complex epistemology that inspired this exercise. Sustainability is a living challenge that asks to be accompanied, not caged.

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