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Illustrating the conflicts between energy poverty and decarbonisation in the energy transition. A case example in Spain

Jose C. Romero[a,*], Pedro Linares[a], Antonio F. Rodriguez-Matas[a], Manuel Perez-Bravo[a]

[a]*Institute for Research in Technology (IIT), ICAI School of Engineering, Comillas Pontifical University, Madrid, Spain*
**Corresponding author: Jose C. Romero*
email: jcromero@comillas.edu

Abstract

The energy transition required to meet decarbonization goals will change dramatically the type of technologies and energy sources used in our economies, as well as the way we consume this energy. This in turn may have a significant impact on typically low-income, vulnerable consumers, which may not be able to carry out the required investments and fuel changes, or may suffer from higher prices. A multi-criteria, multi-stakeholder long-term energy planning model is used in this paper to evaluate how the sometimes conflicting criteria —such as the increase in total system costs and energy poverty after imposing limits on CO_2 and pollutant emissions— and stakeholders' preferences interact when trying to achieve 2050 decarbonization objectives for Spain. Our results show a significant degree of conflict between objectives: energy poverty increases when decarbonization advances, and vulnerable households may not be able to achieve a full decarbonization of their demand due to budget constraints. The conflict between atmospheric pollution and the rest of criteria is also highlighted. Finally, the study also shows how the preferences of certain stakeholders groups, i.e., utilities, regulators, environmentalists and academia, may accentuate these conflicts. We conclude that the efforts toward decarbonization must be accompanied by targeted financial support mechanisms, and robust regulatory frameworks to protect vulnerable households. We also emphasize the need to incorporate social equity considerations into energy planning models and the necessity for continuous monitoring and adjustment of energy policies.

Keywords: Energy Poverty, Energy Sustainability, Energy Transition, Multi-criteria Analysis, Scenario Analysis, Energy Justice

1. Introduction

More than 30 years have passed since Brenda Boardman published her pioneering studies on fuel poverty in England [1]. Since then, substantial academic work has expanded our understanding of this problem, and has led to the proposal of different policies to alleviate it. [2] critically analyze energy poverty policies within the EU, highlighting inconsistencies in definitions and policy effectiveness. [3] propose methodologies for measuring and monitoring energy poverty globally, emphasizing a need for robust indicators tailored to local contexts. [4] focus on the adverse health effects of fuel poverty, reviewing evidence linking inadequate heating to physical and mental health issues. [5] examines the implications of differing definitions of fuel poverty on policy-making, arguing for more precise criteria to improve intervention strategies.

Measurement approaches have evolved, consolidating subjective indicators such as late payments and inadequate home temperature [6], and objective indicators such as the 2M disproportionate expenditure indicator [7] and the M/2 under-spending indicator [8]; or developing additional methods which address additional aspects of energy poverty [9, 10]. Regarding regulatory measures to tackle energy poverty, both short-term mitigation and long-term structural measures [11] have been proposed. Short-term measures include social tariffs [12] and disconnect protections [13], while long-term measures emphasize energy retrofitting of the housing [14].

However, more research is needed to understand how these measuring indicators or alleviation policies will need to be adapted to the profound changes expected in the energy sector in the coming years. The transition towards a sustainable socioeconomic model that mitigates the worst consequences of climate change is in progress [15], with the EU taking a leading role through the European Green Deal, aiming at carbon neutrality by 2050 [16]. This unprecedented (and hugely complex, particularly in non-electrifiable sectors, see e.g. [17]) transformation will have widespread implications, primarily on energy technologies and prices, potentially impacting vulnerable households, which may be required to carry out significant investments (e.g. to change their vehicles or their heating appliances) or to pay more for their electricity.

Several studies have been carried out which simulate the introduction of some of these changes and assess their impact on different population segments. Particularly, some have examined the impact of energy transition policies on vulnerable households, notably in the context of energy poverty. For instance, research shows that households with lower incomes, smaller sizes, or lower levels of education are disproportionately affected by energy poverty during transitions to cleaner energy sources like electricity and gas [18]. Additional work highlights how energy-poor households struggle to access basic energy services under these policies, which can exacerbate social inequalities [19]. Open-access studies have also explored the complex relationship between energy poverty and policy shifts, emphasizing the effects on relative prices and household energy consumption patterns [20]. Moreover, low-carbon policies can worsen energy poverty by increasing household energy expenses, as shown in recent natural experiments [21]. European-focused research provides insights into how energy efficiency measures have been implemented to alleviate the cumulative impact on vulnerable populations [22].

In addition, recent studies have called attention to new actions required to implement EU provisions, emphasizing the use of public funds to prioritize vulnerable households and redesign subsidy programs [23]. Forthcoming research discusses the challenges faced by low-income households in adapting to new energy technologies during the transition [24]. Studies also suggest that climate policies, while reducing carbon emissions, may inadvertently raise energy costs for the most vulnerable groups, underlining the need for more equitable approaches [25]. The European Commission has provided specific guidance on how energy poverty can be addressed through targeted investments and energy efficiency policies to support low-income households [26]. In Spain, the recent National Energy and Climate Plan [27] includes an analysis of the distributional impact of the plan on households, concluding that the effect may be progressive (that is, that it will be more beneficial for lower-income segments). However, these studies are typically limited to a reduced set of policies, and moreover do not take into account the interactions of these policies with other elements of the energy system.

In this paper we incorporate this systemic approach to evaluate the impact that complying with decarbonization scenarios in 2050 may have on vulnerable households. In particular, the research questions that we aim to answer are the extent to which there may be a conflict between decarbonizing our economies and protecting these households (as well as among other criteria for the energy transition), or between the preferences of different stakeholders towards these conflicting criteria. To address these questions, we have developed a multiple-criteria, multi-stakeholder decision making model,

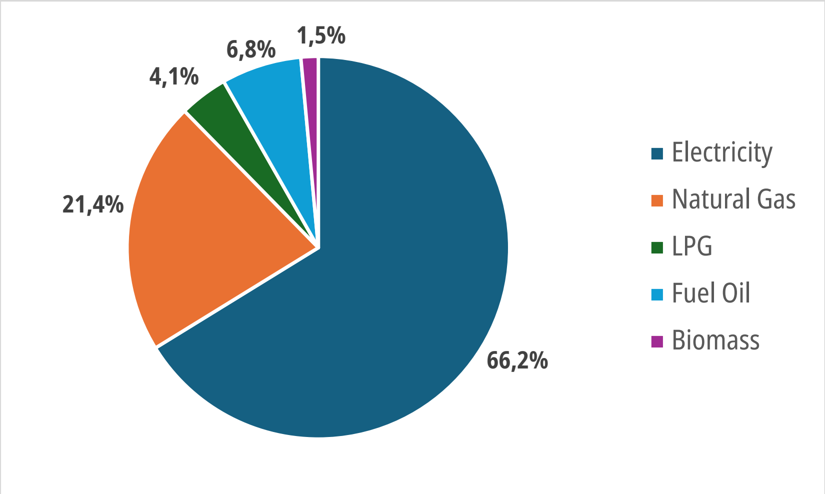

Figure 1: Household expenditure in energy carriers in Spain 2023

based on an open-source, long-term energy planning model [28] which includes energy demand from all sectors in the economy and the different ways in which this demand can be supplied with many different energy sources and technologies. The model finds optimal energy planning strategies according to different criteria including cost, CO_2 emissions, atmospheric pollution, energy security, employment, and of course energy poverty, all within the sustainability framework proposed by [29]. The model also accounts for different, potentially conflicting stakeholders' preferences (regulators, academics, environmentalists, and policy makers). These perspectives are essential in the context of energy planning, as they represent the key groups involved in shaping energy policies. Regulators focus on compliance and the feasibility of implementation, academics provide research-driven insights, environmentalists emphasize sustainability and the environmental impact, and policymakers must balance social, economic, and environmental considerations. By incorporating these diverse viewpoints, the model better captures the complexity of real-world decision-making processes in the energy transition.

In order to assess the impact of the energy transition on energy poverty, we introduce two segments for residential energy demand, based on income levels, to represent vulnerable households. We apply the model to Spain, one of the largest countries in the European Union, with an energy mix and decarbonization policy representative of the EU as a whole. Based on data from INE [30]), in Spanish households' (see 1) energy expenditure is distributed primarily across electricity, natural gas, and other energy sources. Electricity accounts for the largest share at 66.2%, followed by natural gas at 21.4%. Other sources such as liquefied petroleum gas (LPG), fuel oil, and biomass represent smaller shares, with 4.1%, 6.8%, and 1.5%, respectively. This distribution reflects the diverse energy needs of households and the critical role of electricity and natural gas in the overall energy mix. In 2023, energy poverty represented by the indicator of inability to maintain an adequate temperature at home during winter surpassed 20%, highlighting the ongoing severity of the issue [31] in Spain.

Therefore, this exercise allows us to identify the interactions and trade-offs that will appear along the energy transition, in particular regarding decarbonization and energy poverty in a particular case study, i.e., Spain; it also allows to understand the conflicts that exist when different stakeholders' interest are considered. This in turn will help decision-makers understand better how to protect vulnerable households along the energy transition.

The following sections detail the multi-criteria methodology, present the main results of the Spanish case study, and discuss the policy implications of our findings.

2. Methods and data

2.1. Multicriteria model

MASTER.SO is a bottom-up linear optimization model similar to TIMES [32] designed for long term energy planning. The model meets an energy demand at the lowest cost while taking into account technical and environmental constraints, i.e., a limit on CO_2 emissions. It was developed as an optimization model using linear programming [33] and it has been used to test cost-effective decarbonisation policies in Spain [34]. Recently, an open version of the model has been released [28].

The model is designed to solve for a single year, but it also incorporates the possibility of investment decisions. In this setup, the cost of investment is not fully accounted for in the year of the decision. Instead, the annual amortization of the investment is included as a cost in the objective function. This allows the model to capture the effects of investment over time, while still focusing on the outcomes for a specific year.

For this research, a evolution of this MASTER.SO model called MASTER.MC was developed. It uses the basis of the previous model and transforms it into a multi-objective non-linear compromise programming model based on [35][1].

Originally developed by Yu and Zeleny in 1973 [37], compromise programming is a method used to reduce the set of efficient solutions in a decision-making problem. This approach selects the solution from the efficient set that is closest to the ideal point (the point where all attributes achieve their optimal value), while considering the decision-maker's preferences. Thus compromise programming seeks to minimize the distance (using an specific metric) to that ideal point. The MASTER.MC model developed for this research uses this technique to switch the MASTER.SO linear optimization model based on the minimization of a single criterion, i.e., the total cost of the national energy system in a year, into a multi-criteria optimization model.

$$L_p = \left[\sum_{i=1}^{n} [w_i \frac{f_i - f_i^*}{f_{i*} - f_i^*}]^p \right]^{1/p} \tag{1}$$

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[1] A full description of the MASTER.MC model can be found in [36]

Eq. 1 indicates the multi-criteria (compromise programming) objective function that MASTER.MC optimises, where p represents the metric defining the family of distance functions; n is the number of criteria considered; w_i is the preferential weight of the i_{th} objective; f_{i*} is the ideal value for the i_{th} objective and f_i^* is the anti-ideal value for the i_{th} objective.

The distances of greatest interest for compromise programming are those corresponding to the metric $p = 1$, or Manhattan distance, i.e., the standardised and weighted sum of the deviations of each attribute from its ideal value; and the metric $p \to \infty$, or Tchebycheff distance that corresponds to the greatest deviation of the attributes from their ideal value. This in turn corresponds to an utility function that prioritizes the criterion that is furthest away from its optimum.

Interestingly, these two distances represent the limits of the whole compromise set. To get some other intermediate solution, the following formulation can be used:

$$
\begin{aligned}
Min(\lambda L_1 - (1-\lambda)L_\infty) \qquad (2) \\
s.t. \\
f(x) \in F \\
\left| w_i \frac{|f_i^* - f_i^*|}{|f_{i*} - f_i^*|} \right| \leq D, \forall j \qquad (3)
\end{aligned}
$$

This is exactly the formulation adopted by MASTER.MC. Clearly, as long as $\lambda = 1$ the problem becomes Manhattan distance minimization whereas if $\lambda = 0$ it becomes a Tchebycheff's approach.

2.2. Criteria description

This work is rooted on the operational conceptualisation of energy sustainability presented in [29]. Fig. 2 shows the decision tree used. There are three levels in the graph: 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 in the task together with equity; 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

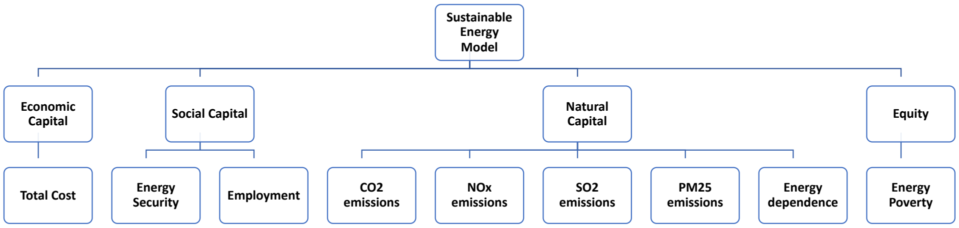

Figure 2: Criteria tree

capital, i.e., emissions of CO_2, $PM_{2.5}$, SO_2, NO_x and energy dependence; and finally, one indicator of energy poverty was chosen to represent equity concerns (strongly connected to the social dimension as well).

Clearly, the choice of these indicators, which was done in a consultation process involving experts, is subject to debate. Further research should either help to consolidate or rule out some or all of these criteria. In the latter case, additional indicators could be suggested and incorporated into the analysis.

Now, a detailed description of the energy poverty criterion will be presented. For clarity purposes, the description of the other criteria was moved to an Annex.

2.2.1. Energy Poverty

The energy poverty criterion consists of calculating the total cost for vulnerable households to cover their energy services in one year. This vulnerable population was assimilated to the MIS-based energy poverty indicator for Spain in 2015, which stood at 7% of the total population [38]. We acknowledge that this reference is subject to modification (indeed, it has increased to around 9% in recent years [39]), but we considered it coherent to maintain this relatively low level, assuming that active policies to combat energy poverty will at least contain its growth. In any case, increasing this percentage would only exacerbate the results of our study, demonstrating that the conflict between decarbonization and energy poverty is even more severe.

The residential energy demand in the model is categorized across various essential services that households require, including space heating, space cooling, hot water, lighting, and the use of household appliances such as fridges, ovens, washing machines, and dishwashers, as well as other electric devices. Each of these categories is met through a variety of technological options, differentiated by their energy sources, efficiencies, and costs. For instance, space heating demand can be satisfied through a range of technologies, including fossil-fuel-based solutions like diesel and natural gas boilers (with variants such as conventional, low temperature, and condensation models), or more sustainable options like heat pumps. These heat pumps vary in their coefficient of performance (COP), and can either be powered by centralized electricity from the grid or distributed sources such as localized generation systems. Biomass furnaces, micro-CHP systems, and district heating solutions are also technological options to satisfy heating demands.

Similarly, space cooling relies on air conditioning systems, with technological options distinguished by their COP and electricity sources (centralized or distributed). For hot water, traditional fossil-based technologies like diesel and gas boilers are considered, alongside electric resistive heating, biomass systems, and solar thermal solutions. Each technology presents different efficiency levels and cost structures, depending on whether the energy is sourced centrally or locally.

In the case of lighting, the model accounts for the transition from less efficient incandescent bulbs to more efficient technologies such as fluorescent and LED lightbulbs. These lighting solutions are powered either by centralized grid electricity or by distributed systems. For household appliances, such as fridges, the model distinguishes between conventional and high-efficiency models, with variations in their energy consumption profiles based on the source of electricity used, whether from centralized or distributed systems.

All these technologies are therefore integrated into the optimization process of MASTER.MC, where both vulnerable and non-vulnerable households are treated separately. The model optimizes the investment and utilization of the most cost-efficient technologies available for each household category. Through this process, MASTER.MC ensures that the energy demands of both vulnerable and non-vulnerable households are met by selecting technologies that balance the multiple criteria described in Fig. 2.

A similar deployment of energy services and technologies is applied by MASTER for other sectors, such as transport, industry, and services. However, it is important to note that only the residential demand, as detailed above, which excludes fuel consumption for transport, is included in the analysis of energy poverty. The focus is specifically on the energy needs that occur within the household, making residential energy demand the core of the energy poverty analysis in this model.

Fig. 3 describes how the MASTER.MC works, including the split in

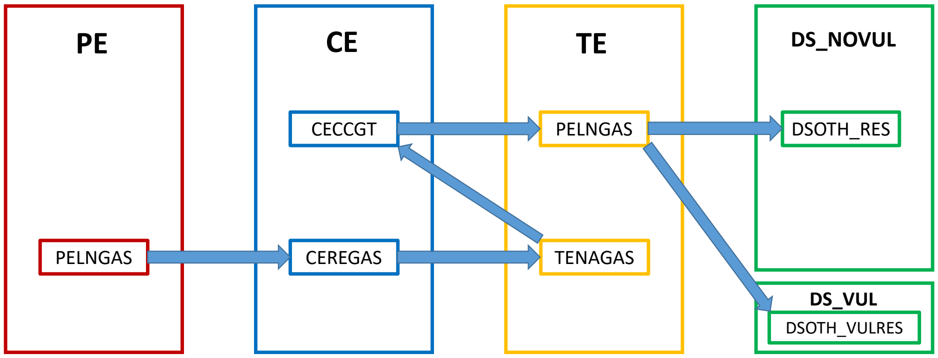

Figure 3: MASTER.MC flow description (based on [33])

energy services mentioned above. Each rectangle represents a column of the model, namely, primary sources (PE), conversion (CE), transport (TE) and demand services (DS). As an example, a specific flow has been added, that of the natural gas that enters in liquefied form to the system, is regasified, then redirected to a CCGT plant where electricity is generated and finally distributed to the residential final demand divided in non-vulnerable and vulnerable households, respectively.

$$\text{Tot\_Cost\_Vul} = \sum_{te,pe} (\text{Consum} \cdot \text{Mean\_Cost})_{te,pe} + \text{Tot\_Inves} \tag{4}$$

Eq. 4 describes the calculation of the optimization variable associated with energy poverty. The formula includes two elements, namely, (1) the costs associated to the consumption of energy through networks (te), e.g., natural gas and electricity, and the costs associated to the consumption of primary energy (pe), e.g., biomass, and (2) the investment in equipment to satisfy energy services at home (Tot_Inves), e.g., appliances, boilers or hear pumps.

The first factor is calculated using the endogenous average cost of different energy sources, primarily natural gas and electricity. The second factor is determined as the annual depreciation value of the corresponding energy equipment.

Thus, the energy poverty criterion that MASTER.MC incorporates as one of its multi-criteria variables will seek to minimize the total cost for vulnerable households in meeting their energy needs. Two elements are considered when calculating the total cost of energy supply for vulnerable households, namely, (1) the consumption of energy in vulnerable households and (2) the depreciation of the investment in equipment in these households. As this is a minimization criterion, the model will seek to make this cost as low as possible, always respecting the technical restrictions and critical limits, and in balance with the rest of the criteria.

2.3. Critical limits

Once the different criteria have been integrated within the multi-criteria optimization strategy, critical limits representing those absolute boundaries that cannot be exceeded in any circumstance are to be included as well. Once again, the energy sustainability conceptualization presented in [29] has been followed in this exercise. In it, three conditions are required to guarantee the sustainable condition of an energy system, namely, (1) creates value, (2) respects critical limits and (3) contributes to a fair distribution of resources. With the incorporation of this critical limits functionality in MASTER.MC we are honoring the second condition.

In this case we have incorporated critical limits only to emissions of CO_2 and to atmospheric pollutants, but the detailed analysis has been set on the former. The constraint that was finally set for CO_2 emissions from the energy sector in Spain in 2050 was 12.8 Mton. This value is consistent with the objective of zero net emissions in that year. It is important to note that this is a critical value for the optimization exercise. As we will see, the stricter we are with this term, the more impact it will have on the optimization of the other criteria including energy poverty.

It is noteworthy that MASTER.MC model allows absolute limits to be incorporated for each and every one of the criteria. An interesting future work would be to define the remaining limits using tentative values obtained through expert consultation and analyze their impact on the results of the optimization.

It is important to note also that the CO_2 price is not treated as an exogenous variable driving decarbonization through price signals, but rather as a critical limit that prevents the model to surpass a certain level of emissions.

2.4. Scenario description

As mentioned above, MASTER.MC is an optimization model that represents the energy system of a country as a whole and that seeks to cover a given demand in an optimal way, taking into account the different additional constraints that are considered.

Hence the present work has focused on the Spanish energy sector in 2050. A base scenario was designed together with some sensitivities with the aim of analyzing possible future configurations of the Spanish energy system in that crucial year in the decarbonization strategy worldwide.

In addition to the demand, the MASTER.MC model uses a large amount of data that makes it possible to represent the nine different criteria considered. A very detailed description of these parameters can be found in [36]. Supplementary material has been made available including the whole dataset of the model.

Neverteheless, in order to provide the reader with the basic information for a proper understanding of the exercise conducted, Table 1 was included. The main reference used for this data is [40]. The authors are aware of the high degree of uncertainty around these parameters. We leave it to future work to incorporate robust optimisation techniques that take these uncertainties into account endogenously [41].

2.5. Preferences of the stakeholders

The methodology to obtain weights for the different criteria involved consulting a variety of stakeholders to gather expert judgment. For this purpose, we selected four experts from four main categories: regulators, academics, environmentalists, and industry representatives. Each group provides a unique perspective on the criteria that should be prioritized in the energy transition. In this regard, it is interesting to note that some of these groups are more active than others in policy making: typically, academics have a lower participation in policy making. Consumer groups are even less represented in the process (and it was indeed impossible to obtain their views for this exercise). This has clear policy implications, since the more active or powerful groups will have their views better represented in actual policy.

The process involved gathering data through structured surveys, to derive weights for each criterion. This approach is supported by methodologies used in similar studies, where expert elicitation is a valuable tool for decision-making in energy policy [42, 43].

Table 1: Inputs MASTER.MC model for Case Study Spain 2050

Type	**Technology**	**Unit**	**2050**
Inversion cost	**Nuclear**	€/kW	4000
	Coal supercritic CCS	€/kW	3000
	CCGT	€/kW	800
	CCGT CCS	€/kW	1300
	OCGT CCS	€/kW	800
	Wind onshore	€/kW	1200
	Wind offshore	€/kW	2000
	PV centralized	€/kW	600
	PV distributed	€/kW	1600
	Solar termoelectric	€/kW	2900
Demand	**Industry (mining, construction and materials)**	GWh	212684
	Industry (chemistry)	GWh	53721
	Industry (others)	GWh	90430
	Primary	GWh	47066
	Services	km^2	845
	Air passengers	Mpkm	27967
	Sea passengers	Mpkm	1063
	Land passengers	Mpkm	432622
	Air load	Mtkm	104
	Sea load	Mtkm	65776
	Land load	Mtkm	423943
	Residential (heat)	GWhHEAT	149699
	Residential (cold)	GWhCOLD	49196
	Residential (hot water)	GWhACS	56148
	Residential (light)	Glmh	1099964
	Residential (appliances)	km^2	769
	Vulnerable Residential (heat)	GWhHEAT	14805
	Vulnerable Residential (cold)	GWhCOLD	4866
	Vulnerable Residential (hot water)	GWhACS	5553
	Vulnerable Residential (light)	Glmh	108788
	Vulnerable Residential (appliances)	km^2	76
	Services (heat)	GWhHEAT	62046
	Services (cold)	GWhCOLD	105091
	Services (hot water)	GWhACS	3101
Demography	**Households**	Million households	20
Fuel prices	**Coal**	€/MWh	9
	Gas	€/MWh	25
	Oil	€/MWh	37
Finance	**WACC**	%	9.00

We understand the limitations posed by the small sample size. Therefore, the results should be interpreted with caution. Our primary objective is to highlight the importance of including diverse viewpoints in the decision-making process and to demonstrate the potential variability in outcomes based on the weights assigned by different stakeholder groups. Similar cautions about the robustness of results derived from small samples have been discussed in other studies [44].

Future research should aim to conduct a more extensive survey to obtain weights that are statistically robust and representative of a broader population. This would involve engaging a larger and more diverse sample of stakeholders, which would help in refining the weights and enhancing the overall robustness of the findings [45].

In summary, while the current study provides valuable insights into the relative importance of different criteria from the perspectives of various stakeholder groups, it is clear that more comprehensive research is needed to solidify these findings. We advocate for further studies that expand on our methodology to ensure that the weights used in energy policy modeling are both reliable and reflective of the wider societal views.

Thus following [46], a survey involving the nine criteria considered in our research was conducted and presented to a group of four regulators, four academicians, four environmentalists and four policy-makers for a pairwise comparison. In this way, sixteen Saaty's matrices were obtained [47]. From these matrices, the corresponding individual weights were found. These sixteen vectors of weights reflect the individual preferences of each expert.

Based on these preferences, and following a goal programming methodology [48], the aggregated preferential weights of the decision-makers for the criteria were obtained, as well as the inconsistency of their value judgments. In this case, once the maximum possible deviation was calculated, two experts whose inconsistency ratio had exceeded 20% were eliminated.

Once the relative weights of the criteria at each hierarchical level were obtained, they were aggregated up to the top level in order to obtain the absolute preferences of the criteria. This was done by multiplying them by the relative preferences at the hierarchically superior level.

Table 2 shows the weights assigned by each group to each criterion once the individual preferences of the third and second levels had been aggregated and corrected using the cross preferences between the different stakeholders. In each column we have the corresponding criteria defined in Fig. 2, i.e., COST: Total Cost; PE: Energy Poverty; CO2: CO2 emissions; DEP: En-

Table 2: Preferences of the Stakeholders

	COST	**PE**	**CO2**	**DEP**	**NOX**	**SO2**	**PM25**	**SEC**	**JOB**
Utility	0.294	0.049	0.049	0.045	0.04	0.045	0.154	0.150	0.179
Academia	0.276	0.009	0.008	0.015	0.02	0.028	0.151	0.034	0.459
Environmentalists	0.291	0.126	0.041	0.041	0.10	0.047	0.154	0.079	0.116
Policymakers	0.338	0.051	0.041	0.042	0.04	0.085	0.242	0.047	0.118
Aggregated	0.227	0.083	0.043	0.046	0.08	0.085	0.152	0.076	0.203

ergy dependence; NOX: NOx emissions; SO2: SO2 emissions; PM25: PM2.5 emissions; SEC: Energy Security; JOB: Number of jobs in the energy sector.

Additional Tables describing the weighting process based on the preferences expressed by the stakeholders can be found in an Annex. Supplementary material including the results and data management of the conducted survey has also been available.

3. Case Study: Spanish Energy System in 2050

This section presents the results of the case study on the Spanish energy system in 2050. We start by analyzing the payoff matrix, the initial point of the multi-criteria study. Next, we show the results of the base scenario, which serves as a reference for comparison with other sensitivity scenarios. These other scenarios are obtained by assigning different weights to the parameters and solving the model using various metrics in compromise programming. We then provide a detailed analysis of the residential sector and vulnerable households within it, which is the central focus of this paper.

3.1. Payoff Matrix

Table 3 presents the 2050 payoff matrix, which is the result of solving the optimization problem by fixing one criterion at a time and leaving the others free[2].

Table 3: Payoff matrix for 2050

Criteria	COST [G€]	PE [G€]	CO2 [Mton]	DEP [%]	NOX [Mton]	SO2 [kton]	PM25 [kton]	SEC [G€]	JOB [Mjobs]
COST	**206.58**	3.53	**12.84**	0.27	**0.13**	4.499	**76.500**	2.48	3.29
PE	257.75	**2.63**	**12.84**	**0.28**	0.12	4.513	**76.500**	**2.67**	3.94
CO2	309.06	5.24	**5.78**	0.12	0.10	4.467	**76.500**	1.77	3.54
DEP	299.42	**6.11**	**12.84**	**0.06**	0.13	4.506	**76.500**	1.11	3.31
NOX	307.64	5.40	**12.84**	0.13	**0.06**	3.856	61.476	1.94	3.38
SO2	277.32	5.15	**12.84**	0.17	0.09	**0.614**	**76.500**	2.63	**2.83**
PM25	286.55	5.18	**12.84**	0.17	0.09	3.705	**34.422**	2.52	2.97
SEC	304.52	5.18	**12.84**	0.07	0.11	4.546	**76.500**	**0.72**	3.47
JOB	**313.42**	4.69	**12.84**	0.24	0.11	**6.895**	**76.500**	1.96	**5.01**

From this payoff matrix, several important insights emerge. First, blue values represent the optimal solution in each row. Second, the behavior of the CO_2 criterion is particularly notable. The 12.8 Mton limit (in red) is a stringent constraint that significantly influences the model. The fact that optimizing other criteria results in exactly 12.8 Mton for the CO_2 criterion indicates that this limit heavily conditions the overall optimal energy system for 2050[3].

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[2] At first, a dominance study was conducted on the matrix and no redundant criteria was found.

[3] The same applies to the $PM2.5$ criterion. This study does not delve deeply into the trade-off between $PM2.5$ and energy poverty; exploring this in future research would be valuable.

3.2. Base Scenario

A base scenario was defined as an L_1 optimization, using the average aggregate substantial increase (Table 2) and the inputs from Table 1.

Table 4: Base scenario for 2050

Criteria	**Values**
COST [G€]	251.15
PE [G€]	3.35
CO2 [Mton]	12.84
DEP [%]	0.19
NOX [kton]	0.07
SO2 [Mton]	1.36
PM25 [kton]	68.64
SEC [G€]	1.14
JOB [Mjobs]	4.03
L1	0.43

Table 4 presents the results of this base scenario.

It is noteworthy that CO_2 emissions exactly match the imposed limit of 12.8 Mton. This has significant implications: as indicated when describing the payoff matrix, this limit prevents the system from achieving optimal values for the other criteria, which would imply higher CO_2 emissions. A sensitivity analysis was conducted to explore this further. When the model was run without an absolute constraint on CO_2 emissions, the energy system emitted 59 Mton in 2050, with a total cost of only 191 G€. The costs for vulnerable households would have been reduced to 2.74 G€, a 18% reduction compared to the base scenario.

Imposing strict emission limits leads to increased system costs, which disproportionately affect vulnerable consumers. These households face higher energy expenses as a result, emphasizing the need for direct support during the energy transition. Utilizing tools like the one developed in this study allows us to identify the magnitude of these impacts and plan accordingly. It becomes evident that without adequate support mechanisms, vulnerable households will bear a heavier burden in the pursuit of decarbonization goals.

3.3. Multi-criteria Comparison

This analysis compared three compromise programming runs varying the target distances, i.e., L_1, L_∞, and an intermediate value ($\lambda = 0.5$).

Figure 4 presents this comparison in the form of a web diagram.

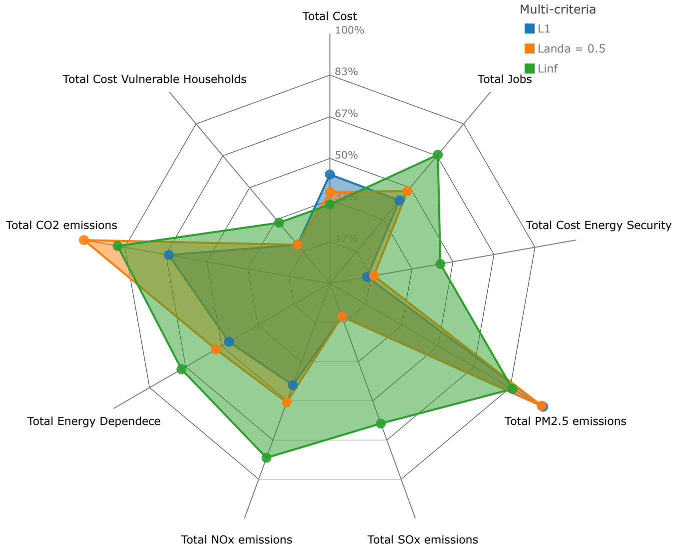

Figure 4: Multi-criteria comparison for 2050

As shown, the L_1 run offers a good balance between the different criteria. In contrast, the L_∞ result, which prioritizes the criterion farthest from its optimum, i.e., $PM_{2.5}$, significantly worsens the performance of most other criteria. This reveals a latent conflict between these two criteria, indicating that prioritizing local pollution mitigation has a significant negative impact on energy costs for vulnerable households.

Moreover, this type of analysis highlights the consequences of choosing different strategies in designing the energy transition. Opting for an efficiency strategy incurs certain costs, which must be addressed. However, choosing a rawlsian equity strategy that prioritizes the most unfavorable criterion results in significantly higher costs for the other non-prioritized criteria. This is a highly relevant consideration in ensuring an energy transition that leaves no one behind.

3.4. Stakeholders Comparison

A second comparative analysis was conducted based on the preferences of different stakeholders. The model was run multiple times, alternating the assigned weights from Table 2.

Figure 5 shows the results of this analysis.

It is particularly interesting to note how the group of environmentalists,

Figure 5: Stakeholders comparison for 2050

by prioritizing environmental criteria, significantly worsens both the total system cost and the energy poverty criteria. This figure highlights the substantial variability in outcomes depending on the priorities set by different stakeholder groups. For example, when the preferences of regulators are prioritized, the model tends to balance between cost and emission reductions more effectively, but with a moderate impact on energy poverty. On the other hand, when the preferences of environmentalists are given higher weights, there is a clear improvement in local pollution and CO2 reduction, but at the expense of significantly higher system costs and a notable increase in energy poverty.

These results underscore the importance of carefully considering whose preferences are prioritized in the policy-making process, as different priorities can lead to vastly different outcomes. This type of analysis is crucial for understanding the trade-offs involved and for designing balanced policies that minimize adverse impacts on vulnerable populations while still achieving environmental goals.

3.5. Residential Comparison

As explained in Section 2, the MASTER.SO model, and by extension the MASTER.MC developed for this study, defines an energy system that covers a given energy demand in a specific country and year, including investment in new capacity if required. This exercise is carried out with a level of disaggregation that ranges from the import of primary energy, through conversion (electricity generation, oil refining, and regasification), to the choice of specific technologies that cover different final energy services demanded in industry, transport, services, and residential sectors. The model includes a dataset with more than three hundred of these technologies.

Each of the runs discussed in the previous sections contains this detailed breakdown in the final services, which is not elaborated here for clarity purposes. A detailed description of these technologies can be found in [36] and [33].

However, a particular focus on the energy sources households use to meet their heating demands is presented here to understand how they react when the nine criteria and corresponding critical limits are considered.

For this comparison, the base scenario was used.

Table 5: Energy sources for residential heating demand in 2050

Source	**Vulnerable households**	**Non-vulnerable households**
Centralized Electricity	87.37 %	100 %
Natural Gas	12.63 %	0 %

Table 5 shows the values obtained.

It is particularly interesting to note that the process of electrification of demand has been completed in non-vulnerable households, as expected for the whole sector in the Spanish Energy Roadmap 2050. However, this has not yet happened in vulnerable households, which continue to use natural gas to meet their thermal needs (12.63%). This percentage would have been much higher if the CO_2 constraint had been relaxed.

Thus, it becomes clear that the strict emission limit forces the model to adopt more costly solutions, particularly impacting the most vulnerable households. These households respond by adopting coping strategies to mitigate the high energy cost scenario[4]. Given that the primary challenge in the

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[4] The MASTER-MC model evaluates the energy system for a specific target year, rather than over a period, and therefore does not explicitly consider the phasing out of older technologies ("vintages") or their decommissioning. Investment decisions are based on the calculation of amortized costs, taking into account the assumed useful life of each device. For this analysis, a useful life of 15 years was assumed for both heat pumps and gas boilers.

electrification of heating demand is investment, these results clearly indicate the need to prioritize vulnerable groups in the allocation of public support for the adoption of these technologies. Ensuring that vulnerable households receive adequate financial assistance for the transition to electrified heating systems is essential for achieving an equitable energy transition.

3.6. Sensitivity Analysis on Vulnerable Households

To complement the analysis, we performed a sensitivity study by modifying the percentages of households considered vulnerable based on two alternative indicators. The first indicator, the "10% rule," identifies energy-poor households as those spending more than 10% of their income on energy expenses. Using this indicator results in a vulnerable population of 15%, reflecting the real situation in Spain in the base year (2015). The second indicator is based on inadequate indoor temperature, which considers households that report being unable to maintain an adequate temperature during winter. To represent the share of vulnerable households under this indicator, we used the highest historical value for Spain, observed in 2023, at 21% of the population. This allows us to evaluate the impact of an extreme vulnerability scenario.

It is important to emphasize that the energy poverty indicator is not calculated endogenously within the MASTER.MC model. Instead, it serves as an external parameter used to segment the population into vulnerable and non-vulnerable groups. This segmentation allows the model to analyze the differentiated impacts of decarbonization policies on these two groups while maintaining the flexibility to test alternative definitions of vulnerability.

The results of this sensitivity analysis are presented in Table 6.

Table 6: Sensitivity analysis: Impact on key criteria for residential heating demand in 2050

Criteria	**Unit**	**MIS (Base)**	**10% Rule (15%)**	**TEMP (21%)**
Total Cost	[GEur]	253.27	252.72	252.69
Cost Vulnerable Households	[GEur]	3.33	7.11	9.95
CO_2 Emissions	[$MtCO_2$]	10.41	10.64	10.80
Energy Dependence	[%]	0.17	0.17	0.17
NO_x Emissions	[$MtNO_x$]	0.09	0.09	0.09
SO_x Emissions	[$ktSO_x$]	1.49	1.50	1.50
PM2.5 Emissions	[ktPM2.5]	75.49	75.92	75.87
Cost Energy Security	[GEur]	1.01	1.01	1.01
Jobs	[MJobs]	4.07	4.19	4.30

As seen in Table 6, the most affected criterion, as expected, is energy poverty. The total cost for vulnerable households increases significantly as the percentage of vulnerable households rises.

Moreover, when comparing the percentage of electrification of the demand, the relative values remain consistent with those presented in Table 5. However, in absolute terms, the dependence on natural gas increases with higher vulnerability levels, reflecting the additional challenges faced in these scenarios.

4. Conclusion and policy recommendations

In this paper we have conducted a prospective study to illustrate the potential conflicts between desirable objectives of the energy transition, namely the decarbonization of the energy system and the protection of vulnerable households. Our approach combines the design, implementation and use of a multi-criteria, multi-stakeholder long-term energy planning model with a disaggregation of demand for vulnerable households, to identify the key criteria and their relative importance, providing an ideal framework to track and plan for these conflicts effectively.

The results clearly show that there is indeed a conflict between these two very relevant criteria. When the future energy system is forced to remain below a very strict CO_2 emissions threshold, vulnerable households face significant cost increases. This results in these households resorting to coping strategies to minimize this cost, which in the example analyzed means keeping their gas appliances (instead of investing in heat pumps)[5]. This in turn prevents the complete decarbonization of the residential sector by 2050. Similar impacts may be expected in terms of transport needs.

Other conflicts illustrated by the exercise include: a trade-off between reducing significantly PM2.5 emissions and all the other criteria for the energy transition (cost, CO_2 emissions, jobs, or energy poverty); and also the different stakeholders' views. In this regard, it should be highlighted how the group of environmentalists, by prioritizing the environmental criteria, significantly worsen both the total system cost criterion, the energy poverty criterion and to a lesser extent employment.

The study presents of course several limitations in terms of, for example, a limited disaggregation of demand according to household income profiles, or a more detailed consideration of both the different demand technologies and some coping strategies of vulnerable households, such as reducing consumption or micro-efficiency actions. The sample of stakeholders considered is also quite small, and should be enlarged for a better understanding of their views. However, and in spite of these, there are two significant conclusions

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[5] The MASTER-MC model evaluates the energy system for a specific target year, rather than over a period, and therefore does not explicitly consider the phasing out of older technologies ("vintages") or their decommissioning. Investment decisions are based on the calculation of amortized costs, taking into account the assumed useful life of each device. For this analysis, a useful life of 15 years was assumed for both heat pumps and gas boilers.

that can be extracted from our study.

The first is that energy modeling exercises (such as those currently being undertaken to develop the EU National Energy and Climate Plans) should include a sufficient disaggregation of demand to understand the systemic impacts that result from the decarbonization of our economies, as well as an explicit representation of different criteria and stakeholders' views and preferences, in particular of those stakeholders which are less represented in the current policy process, such as consumer groups [49]. If not, strategies may be biased, and may not account correctly for the needs of vulnerable households [50].

The second conclusion is that, in terms of the energy transition, there are significant trade-offs and conflicts that must be faced and made as explicit as possible in order to reach a societal consensus that drives the transition. If these conflicts are hidden or minimized, they can be exploited by populist parties which may threaten the required decarbonization of our economies.

In this regard, it is clear that vulnerable households may suffer from the energy transition, and hence must be protected. To mitigate the adverse effects of rising energy costs on vulnerable households observed in our study, we recommend the introduction of targeted financial support mechanisms. This includes expanding social tariffs and heating allowances specifically designed for low-income households, as our results indicate that vulnerable households are disproportionately affected by stringent CO_2 limits. The creation of a robust Social Climate Fund, as proposed by the EU, should be prioritized and adequately funded to ensure it effectively compensates for the increased financial burden caused by the energy transition [11].

Furthermore, improving the energy efficiency of residential buildings is crucial. Our findings show that vulnerable households often adopt coping strategies that deviate from decarbonization targets. Public support to investments in large-scale retrofitting programs aimed at enhancing insulation and upgrading heating systems in low-income housing is mandatory. Such measures can significantly reduce energy consumption and costs for vulnerable households, thereby alleviating energy poverty and aligning with decarbonization goals [51, 52].

Finally, while this study provides valuable insights, further research is needed to explore the detailed impacts of different policy measures on vulnerable households in various contexts. Future studies could focus on incorporating more granular and longitudinal data on household energy consumption patterns, including seasonal variations and regional differences, to better capture the heterogeneity of impacts. Additionally, exploring the role of behavioral factors in energy transition decisions and the effectiveness of targeted policy interventions, such as subsidies, would provide a more comprehensive understanding. Furthermore, investigating innovative financing mechanisms, such as green loans or community-based funding models, could identify pathways to support vulnerable households in adopting cleaner energy technologies and overcoming initial investment barriers. Finally, integrating these aspects a new dynamic version of MASTER model, i.e., openMASTER, capable of considering long-term transitions and technology replacement cycles would provide deeper insights into sustainable decarbonization strategies [53].

In conclusion, achieving a just and sustainable energy transition requires a multifaceted approach that balances decarbonization goals with the imperative to protect vulnerable populations. By implementing targeted financial support, enhancing energy efficiency, integrating social equity in planning, strengthening regulatory frameworks, and conducting continuous monitoring, policymakers can navigate the complex landscape of the energy transition while ensuring no one is left behind.

Appendix A. Criteria description

This annex describes the modelling of the other indicators but energy poverty used in the MASTER.MC model to represent the different criteria to be taken into account in the design of energy transition policies.

Appendix A.1. Total cost

This is the only optimization criterion that the original MASTER.SO incorporated. Similarly to other well known bottom-up models of the energy sector as TIMES or PRIMES, The factors that add up to this total cost are domestic energy production, net import-export, conversion, transport and investment in end-use equipment. Additionally, three additional factors specific to the electricity system were added, i.e. the cost of reserves, the cost of active power and the cost of investing in new capacity.

Appendix A.2. CO2 emissions

The CO_2 emissions criterion has been reformulated, now emissions enter the model in two ways: one as an optimization criterion within the multicriteria framework of compromise programming, and the other as an absolute limit.

$$\begin{aligned}\mathrm{TOTEM} = \mathrm{TOTEM\_PE} + \mathrm{TOTEM\_CE} + \mathrm{TOTEM\_TE} + \\ \mathrm{TOTEM\_FE} + \mathrm{TOTEM\_METHLEAK}\end{aligned} \tag{A.1}$$

Eq. A.1 collects all the elements that are taken into account for its calculation: emissions at import, transformation, end use and methane leakage.

Appendix A.3. Energy Dependence

This criterion of energy dependence tells us to what extent the Spanish energy system depends on non-native sources. Given that in the case of Spain, indigenous sources are essentially renewable, the dependency indicator is transformed in practice into a strong sustainability indicator that shows the non-renewable dependency of the Spanish energy system.

$$\mathrm{EN\_DEP} = \frac{\mathrm{TOT\_ENERGY\_DOMyIMP} - \mathrm{TOT\_ENERGY\_DOM}}{\mathrm{TOT\_ENERGY\_DOMyIMP}} \tag{A.2}$$

Eq. A.2 shows the concrete calculation made.

An alternative to this criterion, to be explored in future research, would be to obtain an indicator of eMergetic dependence instead of energy dependence [54]. To do this, the ratio R/U would have to be obtained, where R represents the renewable eMergy flow and U the total eMergy embedded in the system [55].

Appendix A.4. Local pollutants

These three environmental indicators complement the CO_2 emissions.

On this occasion, the calculation of emissions has been limited to the conversion (EC) and end-use (FE) columns (see Fig. 3).

$$\mathrm{EM\_SO} = \sum_{ds,p,s,l} (\mathrm{D}_{p,s,l} \cdot \mathrm{SOEMFE}_{ds,p,s,l}) + \sum_{ce,te,p,s,l} (\mathrm{D}_{p,s,l} \cdot \mathrm{SOEMCE}_{ce,te,p,s,l}) \tag{A.3}$$

$$\mathrm{EM\_NO} = \sum_{ds,p,s,l} (\mathrm{D}_{p,s,l} \cdot \mathrm{NOEMFE}_{ds,p,s,l}) + \sum_{ce,te,p,s,l} (\mathrm{D}_{p,s,l} \cdot \mathrm{NOEMCE}_{ce,te,p,s,l}) \tag{A.4}$$

$$\mathrm{EM\_PM} = \sum_{ds,p,s,l} (\mathrm{D}_{p,s,l} \cdot \mathrm{PMEMFE}_{ds,p,s,l}) + \sum_{ce,te,p,s,l} (\mathrm{D}_{p,s,l} \cdot \mathrm{PMEMCE}_{ce,te,p,s,l}) \tag{A.5}$$

Eq. A.3, A.4 y A.5 describe the calculation method of aggregating the emissions of each pollutant in each block: p (time periods of the year), s (time subperiods of each period), l (Load levels in each subperiod), and process: ds (demand service), ce (conversion) and te (transport).

Appendix A.5. Energy Security

Energy security has two components: price and quantity. Thus there are two main types of methodologies to assess energy security from an economic point of view: price-based methods and quantity-based methods. Price-based methods consist of measuring the vulnerability of the economy to movements in energy prices, changes that may be abrupt (price shock) or continuous over time (volatility). Quantity-based methods, on the other hand, consist of measuring the economic cost of an energy supply disruption by calculating the welfare loss resulting from a change in energy availability.

Taking as a reference the work of Peersman and Van Robays [56], where a comparison is made of the macroeconomic consequences of different types of oil shocks in a series of industrialized countries (including Spain) is made, in the present investigation an extra cost for crude oil of 4.3 € /MWh has been assigned, a value that has served as a reference to scale up the rest of the prices of energy raw materials.

$$\begin{aligned}\mathrm{PEIMPSECCT} = &\sum_{rg,pe,p,s,l} (\mathrm{QPWR}_{rg,pe,p,s,l} \cdot \mathrm{D}_{p,s,l} \cdot \mathrm{PEIMPSECCT}_{pe,rg}) \\ &+ \sum_{dr,pe,p,s,l} (\mathrm{QPWR}_{dr,pe,p,s,l} \cdot \mathrm{D}_{p,s,l} \cdot \mathrm{ECOVSECPEDOM}_{pe})\end{aligned} \tag{A.6}$$

$$\mathrm{TEIMPSECCT} = \sum_{rg,te,p,s,l} (\mathrm{QPWR}_{rg,te,p,s,l} \cdot \mathrm{D}_{p,s,l} \cdot \mathrm{TEIMPSECCOST}_{te,rg}) \tag{A.7}$$

$$\mathrm{TOTSECCT} = \mathrm{PEIMPSECCT} + \mathrm{TEIMPSECCT} \tag{A.8}$$

Thus, following Eqs. A.6, A.7 and A.8, the energy security criterion is calculated as a monetary surcharge for the system.

It is important to clarify that this extra cost is artificial, i.e. it is not added to the total cost criterion and therefore does not affect its optimisation. Their incorporation into the analysis is through the multi-criteria approach within the compromise programming described above.

In future research this reference value of 4.3 € /MWh for oil could be revised, so that other effects associated with energy security beyond the price shock, namely volatility (from the perspective of price analysis), or loss of welfare resulting from a change in energy availability (quantity point of view) can be incorporated.

Appendix A.6. Total jobs

This criterion is intended to incorporate another key social variable in the analysis: the contribution of the energy sector to the labour market. For this purpose, direct and indirect jobs have been estimated.

For the former, we have focused on the conversion sector, including both the costs of new construction and operation and maintenance. In this case, data from the Institute for Sustainable Futures report in 2015 have been used [57].

For the latter we focused in the services sector, specifically in technologies that cover energy demand for end use. In this case a new parameter has been calculated in the model, i.e. ESSTJOBPACTUY, "Energy Service Supply Technology JOBS per Activity Unit, Yearly" which functions as an employment factor associated with each energy service supply technology (ESST) in the model. This figure has been calculated by dividing the number of jobs per sector according to INE statistics by the NPV of that sector.

$$\mathrm{OFVP\_CONSJOB} = \sum_{ce} (\mathrm{NEWINSTALLCAP}_{ce} \cdot \mathrm{CECONSJOB}_{ce}) \quad \text{(A.9)}$$

$$\mathrm{OFVP\_OPJOB} = \sum_{ce} (\mathrm{TOTACTIVECAP}_{ce} \cdot \mathrm{CEOPJOB}_{ce}) \quad \text{(A.10)}$$

$$\mathrm{OFVP\_ESSTJOB} = \sum_{esst,p,s,l} (\mathrm{QACTESST}_{esst,p,s,l} \cdot \mathrm{ESSTJOBPACTUY}_{esst}) \quad \text{(A.11)}$$

$$\mathrm{OFVA\_JOBS\_P23} = (\mathrm{OFVP\_CONSJOB} + \mathrm{OFVP\_OPJOB} + \mathrm{OFVP\_ESSTJOB}) \quad \text{(A.12)}$$

Eq. A.9, A.10, A.11 and A.12 are those used for the calculation of the criterion.

Appendix B. Preferences

Table B.7 shows the preferences of each group assigned in the second level, i.e., capitals and equity of 2.

Table B.8 shows the cross preferences expressed by the different stakeholders with respect to each other.

Table B.7: Second level preferences

Group	**Economic Capital**	**Natural Capital**	**Social Capital**	**Equity**
Utility	0.294	0.224	0.304	0.179
Academia	0.316	0.106	0.229	0.349
NGO	0.023	0.627	0.186	0.164
Regulator	0.324	0.348	0.246	0.082
Aggregated	0.239	0.326	0.241	0.193

Table B.8: Preferences among stakeholders

Group	**Utility**	**Academia**	**NGO**	**Regulator**
Utility	0.360	0.308	0.249	0.444
Academia	0.247	0.115	0.317	0.080
NGO	0.179	0.389	0.222	0.256
Regulator	0.213	0.188	0.213	0.221

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