A multi-criteria approach to local energy planning: the case of Barreiro municipality

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Keywords: Local Energy Planning, Multi-criteria Evaluation, MACBETH.

Abstract: Energy planning is at the top priorities of local authorities nowadays. Problems such as the depletion of natural resources, the wellbeing of human population and the security of energy supply have became the main drivers to change the current fossil fuel-based energy paradigm. In order to put into practice energy planning processes at the local level, there is a need to provide support methods and tools to local authorities. In this paper we present a decision support methodology for sustainable local energy planning that combines energy modelling and multi-criteria evaluation techniques. The focus of the paper is on the building process of a multi-criteria evaluation model for the municipality of Barreiro, in Portugal. The municipality case revealed that multi-criteria evaluation is a suitable tool for local energy planning.

1 INTRODUCTION

Today's energy systems are largely driven by the combustion of fossil fuels, which cause negative impacts in the environment, in the society and in the economy. Impacts such as the greenhouse gases (GHG) emissions are considered to be the principal cause of climate change (IPCC, 2007). The depletion of natural resources affects the ecosystems and the wellbeing of human population, and the risks on the security of energy supply due to the dependence of a country in imported fossil fuels affect negatively the economy.

Energy challenges encompass an urgent change of the current fossil fuel-based energy paradigm and the promotion of sustainable energy systems. It is recognized nowadays that local authorities have an important role to play in the promotion of sustainable energy systems. Indeed, recent policies and initiatives, such as the Covenant of Mayors and the C40 Cities, stress the fact that cities *are important* actors for implementing sustainable energy policies and that their actions must be encouraged and supported. The emerging calls for action at the local level must be accompanied by methods and tools to assist local authorities in their processes of energy planning. In particular, local authorities need a decision support methodology to help them identifying their fundamental objectives and selecting actions to achieve these objectives.

This paper presents the application of a decision support methodology for energy planning to the municipality of Barreiro in Portugal. The methodology was applied combining energy modelling and multi-criteria evaluation techniques. The focus of the paper is on the building process of the multi-criteria evaluation model. Problem structuring methods such as causal mapping (Bryson et al., 2004) were employed in order to identify the objectives of sustainable energy planning.

The application of the methodology to the municipality of Barreiro encompassed the task of energy modelling for the base year 2008 and for the time horizon of 2020 in a business-as-usual perspective. In this way, it was possible to see the expected evolution in terms of energy consumption and GHG emissions. Afterwards, the selection of a set of actions allowed the generation of alternative energy action plans that were evaluated with the multi-criteria model. In this work, it was adopted a MACBETH socio-technical approach (Bana e Costa and Vansnick, 1999; Bana e Costa et al., 2011; see also Bana e Costa et al., 2008, for an application in the energy sector, and Bana e Costa and Oliveira, 2002, for an application in a municipality) involving actors from the Barreiro City Council and the Barreiro energy agency (S.Energia), who built a value function for each objective and weight the objectives in an one-day decision conference (Phillips, 2007). At the end of the decision conference it was possible to obtain an overall benefit value score for each alternative energy action plan under evaluation. The expected result of the application of the methodology is to provide support to decision-making in local energy planning processes.

The next section presents the structuring of the local energy planning problem, where the objectives and respective attributes are identified as well as the actions and the generation process of alternatives to be subjected to the multi-criteria evaluation. It is also presented how the local actors were involved in this process Section 3 focuses in the building of the multi-criteria evaluation model for the municipality of Barreiro. Section 4 draws some conclusions.

2 STRUCTURING THE LOCAL ENERGY PLANNING PROBLEM

2.1 Identification of Objectives and Attributes

The process of structuring the objectives aims to provide a deeper understanding of the decision context. The objectives were identified through a literature review and through interviews with local actors. Each interview made with a single actor lead to a cognitive map, which represents “a person’s thinking about a problem or issue” (Eden, 2004, p. 673). The individual cognitive maps were subsequently merged into a group causal map (Bryson et al., 2004), which was validated by the interviewees with minor changes. The objectives were then structured according to the procedure described by Keeney (2007). This allowed separating the fundamental objectives from the means objectives. To do this, for each objective, we asked “Why is this objective important in the decision context?” (Keeney, 2007, p. 114) If the response to the question identified that the objective was important because of its implications for some other objective, this was a means objective. If the response was that the objective was one of the essential reasons for interest in the situation, this was a candidate for a fundamental objective.

Figure 1 presents the objectives hierarchy, where the fundamental objectives (in the grey boxes) were used to build the multi-criteria evaluation model.

Table 1 summarizes the selected objectives and their attributes for local sustainable energy planning. Observe that the attributes (that are also known as *descriptors of performance*; see Bana e Costa et al., 2008) are used to measure the extent to which the objectives are achieved by alternative sets of actions (Keeney, 2007).

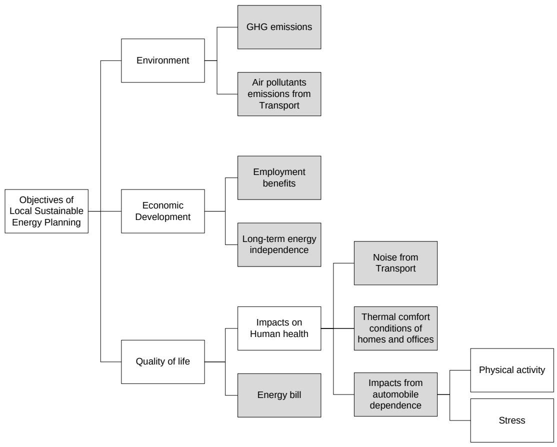

Figure 1: Objectives hierarchy.

Table 1: Objectives and attributes.

	Objectives	Attributes
O1	Reduce GHG emissions	Tonnes of CO_2 equivalent reduced
O2	Reduce air pollution from transport	Tonnes of NO_x emissions reduced
O3	Maximize employment benefits	Net jobs gained
O4	Improve long-term energy independence	Tonnes of oil equivalent of imported fossil fuels reduced
O5	Minimize the negative impacts on human health caused by noise from transport	Number of people that benefit from noise levels reduction
O6	Minimize the negative impacts on human health by improving the thermal comfort conditions of homes and offices	Tonnes of oil equivalent (final energy) reduced for space heating and cooling
O7	Minimize the negative impacts on human health caused by automobile dependence	Number of passenger-km shifting from passenger cars to public transit, walking and cycling
O8	Reduce the energy bill	Euros saved per household per year

2.2. Identification of Actions and Generation of Alternatives

The identification of actions was based on an extended literature review, having into account three selection criteria:

- Local authority actions – the main focus of this work was on the demand side, because it is where the local authority can have a greater power to act. The areas where the local authority has no control of intervention were excluded from this work, such as large-scale energy supply and industry.

- Technical actions – leaving the policy actions or promotion mechanisms outside of the scope of this work.
- Community-scale actions – the focus of this work is community-wide and Government operations only.

Alternatives represent means of achieving the objectives. They usually are a mutually exclusive set of means among which a choice is possible. In general, to be allowed not to choose is also considered an alternative (Zeleny, 1982, chap. 4).

In this case, alternatives are combinations of 26 actions (10 actions in the households sector, nine actions in the services sector, and seven actions in the transport sector) in six different degrees of implementation. Making all the possible combinations between the actions and the possible degrees of implementation would result in a very large number of alternatives (precisely, 6^{26}). Although, it would be possible to generate them with the help of a computer-based decision support system it would be impractical due to the existence of synergies between actions that needed to be analysed. Therefore, it was decided to adopt a pragmatic approach for the generation of alternatives based upon a strategy-generation table procedure (Kirkwood, 1997; Matheson and Matheson, 1998).

The actions and their degrees of implementation were combined directly in the energy model implemented in a Microsoft Excel spreadsheet, allowing in this way to account for the synergetic effects. The rows of the table represent the different degrees of implementation for the different actions that are presented in columns. The only exception is the first row (named "Maintain") that means "do not implement the action". The user builds an alternative by selecting one cell from each of the 26 columns. Figure 2 shows a screenshot of the spreadsheet where the degrees of implementation of the 10 actions of the sector of households for alternative 1 are shown. At the end, the user can visualise if the selected combination of actions/degrees of implementation respect the constraint of GHG emissions reduction (in this case a minimum level of 20% is required). If not, the user should redefine the selection of actions/degrees of implementation in order to accomplish the target reductions in GHG emissions.

The adoption of the strategy-generation table approach for the generation of alternatives provides a structured procedure to sort out alternatives that the user considers to make sense to analyse in more detail. The energy model allowed the creation of five alternatives that were subjected to a multi-criteria evaluation process.

2.3 Involvement of the Local Actors

The involvement of local actors took place in two stages. First, the process of identification of the objectives had the participation of the City Councilman for Environment of Barreiro City Council and the director of the energy agency (S.Energia). This process also involved the participation of local actors from other municipalities in Portugal. Second, a decision conference was held with the participation of two technicians from the Environmental Sustainability Division of Barreiro City Council and two technicians and the director of the energy agency. The actors involved represented the points of view of those two organizations concerning the implementation of the sustainable energy action plan.

CUSTOMIZE MEASURES FOR BUILDING ALTERNATIVE 1

	Households									
Name Alternative 1	Building's heating needs	Water heating fossil fuel shift to solar	Water heating fossil fuel shift to Renewable DHC	Space heating shift of electric heaters to natural gas	Space heating shift of electric heaters to heat pumps	Space heating fuel shift to solar	Space heating fuel shift to Renewable DHC	Space heating shift of fireplaces to pellet stoves	Refrigerators and Freezers' efficiency	Building-Integrated Renewable Electricity generation
Policy reform	Maintain	Maintain	Maintain	Maintain	Maintain	Maintain	Maintain	Maintain	Maintain	Maintain
	Decrease 10%	Shift 15%	Shift 10%	Shift 10%	Shift 10%	Shift 10%	Shift 10%	Shift 10%	Shift 10% to A+ and A++	Increase 10%
	Decrease 20%	Shift 30%	Shift 20%	Shift 20%	Shift 20%	Shift 20%	Shift 20%	Shift 20%	Shift 20% to A+ and A++	Increase 20%
	Decrease 30%	Shift 45%	Shift 30%	Shift 30%	Shift 30%	Shift 30%	Shift 30%	Shift 30%	Shift 30% to A+ and A++	Increase 30%
	Decrease 40%	Shift 60%	Shift 40%	Shift 40%	Shift 40%	Shift 40%	Shift 40%	Shift 40%	Shift 40% to A+ and A++	Increase 40%
	Decrease 50%	Shift 75%	Shift 50%	Shift 50%	Shift 50%	Shift 50%	Shift 50%	Shift 50%	Shift 50% to A+ and A++	Increase 50%

Figure 2: The strategy-generation table.

During the decision conference, a facilitator guided the decision process helped by an analyst. The facilitator started by remembering the model structure created until then, namely by presenting the objectives and their attributes. The facilitator also had the task of stimulating the group discussion concerning the development of the multi-criteria value model without contributing to the content of discussion (Phillips, 2007). The analyst used the decision support system M-MACBETH (*www.m-macbeth.com*) to display on-the-spot the model being developed.

3 BUILDING THE MULTI-CRITERIA EVALUATION MODEL FOR THE MUNICIPALITY OF BARREIRO

3.1 Building a value function for each objective

The objectives and attributes presented in table 1 were used in the model of the municipality of Barreiro after having the agreement from the local actors involved. The exception was in the objective "Reduce noise impacts from transport", which was dropped from the model due to lack of data.

For each attribute the group was asked to define a "neutral" reference level; this means to define a performance that would be neither positive nor negative in the linked objective. The group was also asked to define a "good" reference level for each attribute, i.e. a performance level considered significantly attractive in the light of the objective. Figure 3 shows the performance reference levels defined upon each attribute.

Afterwards, more levels were added to the attributes such that each attribute had four performance levels equally spaced in the attribute scale.. The group was then asked to judge the differences in attractiveness between each two levels of performance, choosing one of the MACBETH semantic categories: *very weak, weak, moderate, strong, or extreme*. For each objective, the process was initiated by asking the difference of attractiveness of changing from the "neutral" performance level to the "good" performance level and followed by asking the difference between each two of the other levels. Figure 4 presents the group judgments matrix for the objective "Maximize employment benefits".

	225	150	75	0
225	no	moderate	strong	v. strong
150		no	moderate	strong
75			no	moderate
0				no

Figure 4: MACBETH judgements matrix for the objective "Maximize employment benefits".

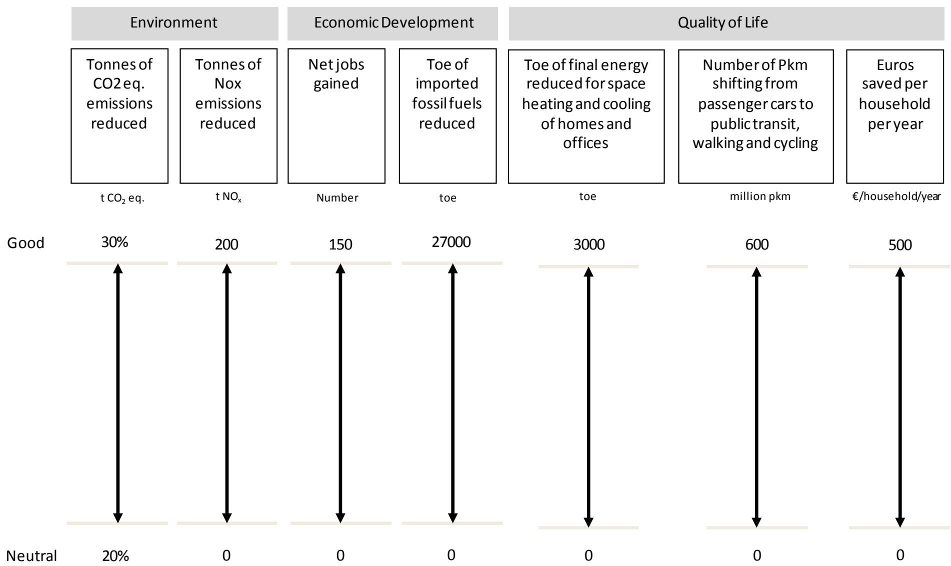

Figure 3: Reference levels "Good" and "Neutral" defined on each attribute.

The M-MACBETH decision support system proposes a numerical value scale based on the set of qualitative judgments inputted in the matrix of judgments (figure 4) using linear programming (see details in Bana e Costa et al., 2011). The numerical scale is anchored on the two predefined reference levels (neutral and good) to which were assigned the scores 0 and 100. The proposed MACBETH scale is then subjected to group analysis and discussion in terms of proportions of the resulting scale intervals. In the case of Barreiro, the group decided to make minor scale adjustments on the value scales of some objectives. Figure 5 represents the value functions obtained for the objectives after the group discussion.

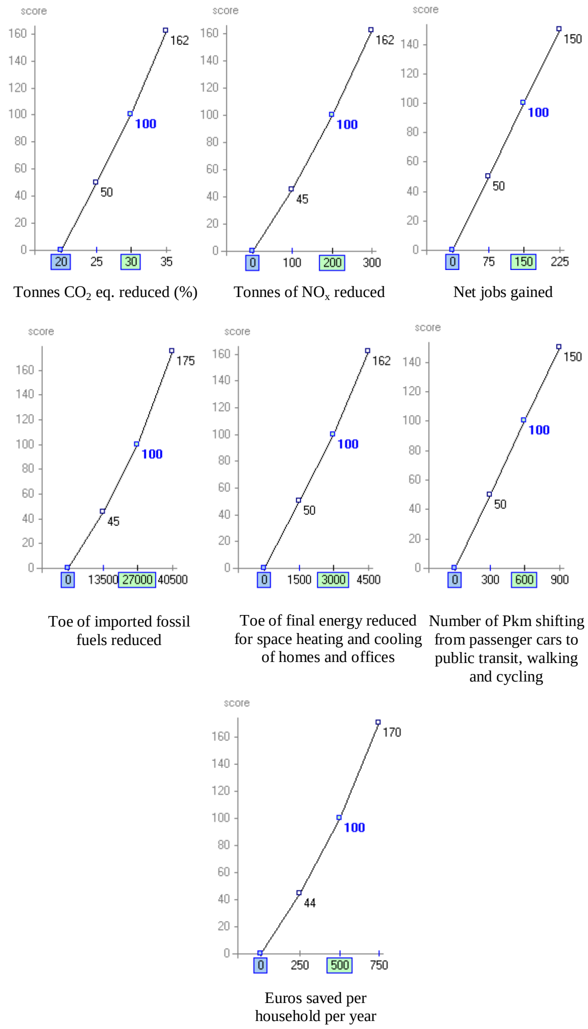

Figure 5: Value functions for the objectives.

3.2 Weighting the Objectives

The relative weights for the seven objectives were defined using the MACBETH weighting procedure. The group was first asked to rank the “neutral-good” swings by their overall attractiveness. The facilitator started by asking the question: “From the seven objectives, if you could choose just one objective to change from a neutral performance to a good performance which objective would you choose?” The questioning procedure continued till the final ranking of “neutral-good” swings was achieved. During the MACBETH questioning procedure to fill in the weighting judgements matrix, the group engaged in a deeper thinking and discussion about the relative importance of the “neutral-good” swings and decided to change the ranking of the second, third and fourth most attractive swings. The final ranking of the “neutral-good” swings is presented in figure 6.

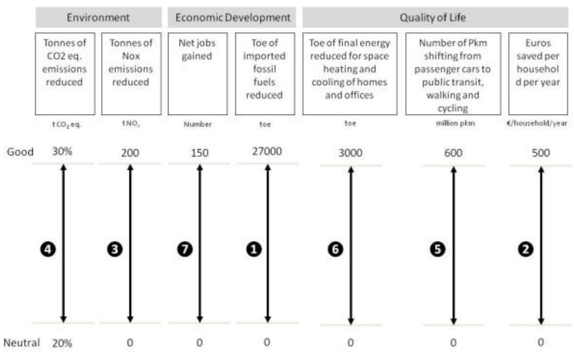

Figure 6: Final ranking of the swings.

The next step consisted in asking the group to judge the overall attractiveness of each “neutral-good” swing, which allowed filling in the last column of the MACBETH matrix in figure 7. Subsequently, the group was asked to pairwise compare the most attractive swing to the second most attractive. The pairwise comparison continued between the most attractive swing and each of the other swings till filling in the first row of the MACBETH matrix (figure 7). Afterwards, judgments concerning the comparison of each two consecutive swings were also made and the questioning procedure stopped. It was not necessary to ask more judgments, once MACBETH is able to create the weighting scale with the information already present in the matrix of judgments (see figure 7).

	[ImpEnergyInd]	[RedEnergyBill]	[RedAirPolTrans]	[Reduce GHG]	[Red AutoDep]	[ImpHumHealthTh]	[MaxEmploytBen]	[Neutral all over]
[ImpEnergyInd]	no	very weak	very weak	vweak-weak	weak-mod	mod-strg	v. strong	extreme
[RedEnergyBill]		no	very weak	positive	positive	positive	positive	positive
[RedAirPolTrans]			no	weak	positive	positive	positive	extreme
[Reduce GHG]				no	weak	positive	positive	extreme
[Red AutoDep]					no	moderate	positive	v. strong
[ImpHumHealthTh]						no	strong	positive
[MaxEmploytBen]							no	moderate
[Neutral all over]								no

Figure 7: The MACBETH weighting matrix.

Figure 8 presents the weighting scale proposed by M-MACBETH. The facilitator asked the group to check the resulting weights in order to validate them. For example, the facilitator asked if the "neutral-good" swing on objective "GHG emissions reduction potential" is worth four times the "neutral-good" swing on objective "Maximize employment benefits" (note that the weights of these objectives are 16% and 4%, respectively), and also if the "neutral-good" swing on objective "Improve long-term energy independence" is worth 1.9 times the neutral-good swing on objective "Minimize the negative impacts on human health by improving the thermal comfort conditions of homes and offices", which the group agreed.

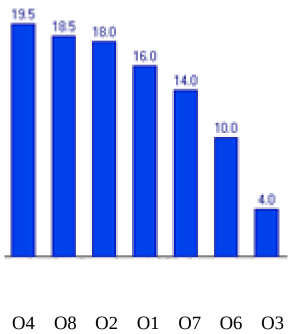

Figure 8: Weighting scale obtained for the objectives presented in table 1.

3.3 Aggregation and Robustness Analysis

The performances of the six alternatives upon each of the objectives were determined in the energy model developed in the spreadsheet and were then inputted in M-MACBETH. The decision support system transformed these performances into benefit scores, using the value functions previously built, and determined an overall benefit score for each alternative by weighted summation of its value scores. At the end of the decision conference, it was possible to visualize the overall benefit scores for the six alternative sustainable energy action plans created (see column "Overall" in figure 9).

The alternative A4 ranked first with 143.83 benefit units and alternative A3 ranked second with 128.25 benefit units. Both A4 and A3 obtained overall scores higher than that of a hypothetical alternative "Good all over", which shows that they are very attractive alternatives. The remaining alternatives also had positive overall scores, i.e. higher scores than that of a hypothetical alternative "Neutral all over", which means that all of them are globally attractive.

Given the hesitations the group had during the weighting process it is wise to analyze if A4 would continue to rank first when the weights are modified. A robustness analysis made with M-MACBETH considering variations of ±3% on the weights of all objectives revealed that A4 continues to be the most attractive alternative from the set of six alternatives evaluated (figure 10).

Options	Overall	Reduce GHG	RedAirPolTrans	MaxEmploytBen	ImpEnergyInd	ImpHumHealthTh	Red AutoDep	RedEnergyBill
A4	143.83	211.60	103.10	74.67	141.89	82.17	100.00	208.36
A3	128.95	100.00	136.58	74.67	103.06	90.57	100.00	228.24
[Good all over]	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
A2	90.16	30.00	106.20	57.33	80.90	96.67	80.00	147.60
A6	78.95	10.00	51.05	50.67	77.45	69.83	80.00	177.56
A1	51.60	0.00	39.15	34.67	74.44	87.57	60.00	62.14
A5	49.93	0.00	48.30	42.00	75.48	88.97	40.00	55.87
[Neutral all over]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Weights :		0.1600	0.1800	0.0400	0.1950	0.1000	0.1400	0.1850

Figure 9: Overall benefit scores of the alternatives.

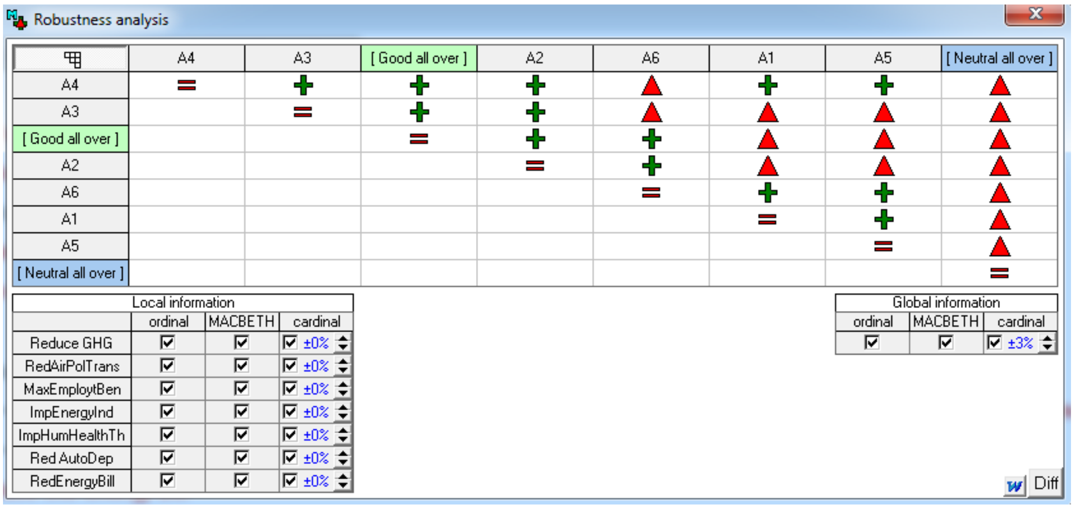

Figure 10: Robustness analysis.

Observe that a green cross in a cell of figure 10 means that the alternative in row additively dominates the alternative in column (in this case the dominance relationship depends on the constraints defined upon the parameters of the additive model), and a red triangle indicates dominance in the classic sense (the alternative in row is always preferred to the alternative in column irrespectively of the constraints defined upon the parameters of the model).

4 CONCLUSIONS

This paper had a particular focus on the multi-criteria evaluation process and its application to the municipality of Barreiro in the context of energy planning. The multi-criteria evaluation model presented is part of a comprehensive decision support methodology which includes also an extensive work on energy modelling of the local energy system. The energy modelling was developed in Microsoft Excel and has several features necessary to the multi-criteria evaluation, namely the process of generating alternatives and the quantification of the performances of the alternatives in each objective (which are required inputs to the additive model developed with M-MACBETH). We underline that the developed model not only allowed to identify which alternative performed best out of six alternatives, but also allowed to verify that it is a very attractive alternative by comparing its overall benefit score with those of the two reference profiles – “good all over” and “neutral all over”. Indeed, in this context, selecting the best alternative of a set of unattractive alternatives would not be a wise decision to make.

With respect to the multi-criteria evaluation process, it is possible to conclude that this is a suitable tool and with great potentiality to be applied to local energy planning processes. In particular, it promotes the participation of several local actors and stimulates thinking and discussion about the key issues for energy planning in their contexts. The decision conference process and the M-MACBETH software used were of valuable help to implement the multi-criteria evaluation.

The development of the methodology had in mind its replication for any local context, as so it is expected that more municipalities will adopt this common methodological framework in the elaboration of their sustainable energy action plans.

Future research will still cover the assessment of investment costs for each alternative to be traded-off with the overall benefits of the alternatives.

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