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Impact Chains and a Multi-Criteria Decision Analysis Tool to Support Electricity Planning

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Abstract: The topic Sustainable Development has brought a wide discussion across a number of sectors in our society, namely in Power Systems. Given the need to address other concerns than the economic ones, decision makers must take into account the rationale that lies beneath strategic choices, such as investing in generation technologies using renewable energy or rather doing business as usual and installing fossil fuel power plants. In this research, firstly, logic models were used as a decision-aid supporting tool, with the aim of contributing to explain the connection between building a given power plant and assessing its possible impacts in terms of sustainable development. All the electricity generation technologies were grouped in thermal, renewable energy sources (RES) and nuclear. The results of the literature review and of a set of interviews with experts, based on the diagrams, allowed to conclude that the use of RES have wider positive social impacts on the long run, despite their short-term higher costs compared to the traditional groups (nuclear and thermal). Secondly, a Multi-Criteria Decision Analysis (MCDA) tool was designed to support the evaluation of different electricity production scenarios. The MCDA tool is implemented in Excel worksheet and uses information obtained from a mixed integer optimization model, to produce a set of optimal schemes under different assumptions. Given the input, the MCDA allowed ranking different scenarios relying on their performance on 13 criteria covering economic, job market, quality of life of local populations, technical and environmental issues. The criteria were weighted using both direct weights and trade-off analysis. This research also presents scenarios for the Portuguese power generation system in 2020, as well as the results of the evaluation using the MCDA tool, relying in the inputs from a group of academics with background in economics, engineering and environment.

Keywords: Energy decision making, electricity generation, logic models, MCDA.

1. Introduction

Among the strategies envisioned by the European Union, two of them concern especially power systems: the 20-20-20 and the European Union Sustainable Development Strategy (EUSDS).

1. The EUSDS aims the building of a European Union respecting the inter-generational principle, while achieving full employment through a competitive social market economy and balanced economic growth, among other objectives [1].

2. The 20-20-20, with a horizon of 2020, points to a reduction of 20% of primary energy consumption with the improvement of energy efficiency, a minimum share of renewables energy of 20% and the reduction of greenhouse gases to 20% below the 1990 values.

The authors addressed in past works social issues in power systems planning [2] [3]. From the literature reviewed related to electricity generation they concluded that the methodologies explicitly expressing economic, social and environmental criteria, fall mostly on Multi-Criteria Decision Aid

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(MCDA). It is clear in the literature that ultimately the economic and environmental criteria still prevail, given the ”soft” aspects of the social issues. Additionally, given the inter-relation between different groups of criteria (and the expression ”socio-economic” proves it) situations exist where some short term non-optimal cost choices can be supported under the perspective of inducing virtuous cycles of social welfare and long-run economic return, as it is advocated, generally, by many who support investment on renewables.

In these terms becomes necessary to organize the rationale behind the support of the strategic importance tat different groups of electricity generation technologies assume. This research aims to give a contribution to this issue, by exploring the construction of diagrams for allowing the visualization of impact chains associated with different technologies. Section 2 addresses this topic. Three logic models (one for each group of electricity generation technology: thermal, nuclear and renewables) were constructed from interviews with experts in power systems and also from document review (consultant reports and government strategy documents).

The research is complemented in section 3, with a Multi-Criteria Decision Analysis tool, created to be used in the evaluation of different electricity generation scenarios. When using multi-criteria decision methodologies, one has to have in mind that best solutions are not universal best solutions, since results are made upon personal judgement of different criteria. In the present work a panel of experts on energy systems was invited to map the diversity of opinions and the outcomes of the use of the MCDA tool, which was demonstrated for the evaluation of possible scenarios drawn for Portugal in 2020.

The criteria used in the MCDA cover not only social, cost and environmental issues, but rather incorporate them in the wider goal of choosing a technically feasible solution. The criteria were drawn from both interviews described in Section 2 and from the literature.

Figure 1 summarizes the methodology used for Section 3. The two main blocks of the methodology are Scenario Generation and Scenario Evaluation (MCDA Tool). Sections 3.1 and 3.2 are dedicated to each one of them. The remainder of this section overviews power generation in Portugal.

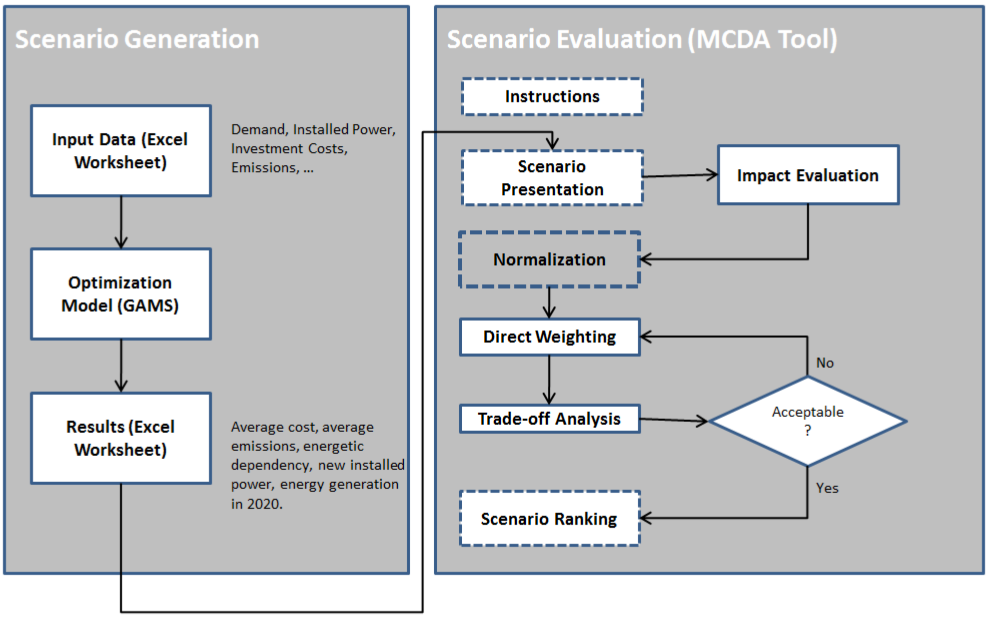

Figure 1: Evaluation of scenarios for electricity production, with MCDA evaluation

1.1. Power Generation in Portugal

Electricity in Portugal is mainly generated from large hydro, thermal and wind power, as can be seen in Figure 2. Thermal power is mostly provided with coal and CCGT (combined cycle gas turbines) power plants. Special Regime Production include all the technologies benefiting from feed-in tariffs, which are in Figure 2 divided in Wind power and ”Other SRP”.

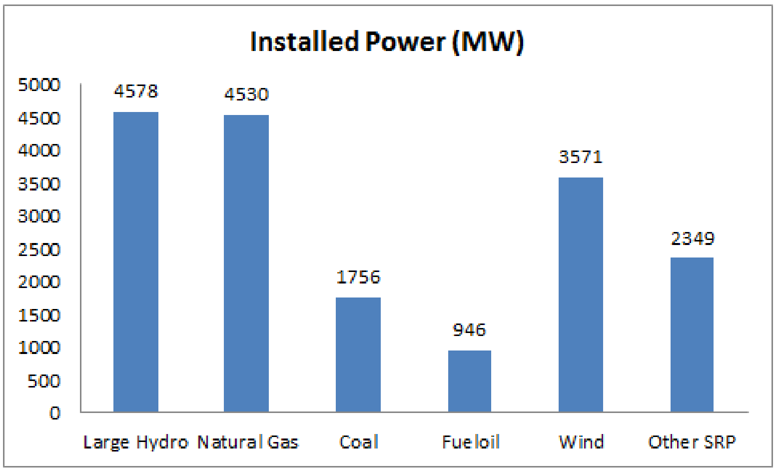

Figure 2: Installed power in Portugal, 2010. Own elaboration from www.ren.pt data. ”Other SRP” include non-renewable and renewable cogeneration, biomass, small hydro, photovoltaics and wave power.

The Portuguese electricity system is strongly influenced by the rainfall characteristics. Although the large hydro power installed capacity remained almost unchanged between 2006 and 2010, in fact the hydro production suffered strong variations.[1]

In 2007, the Portuguese state launched a new plan for installing more hydro power, known as PNBEPH (Plano Nacional de Barragens de Elevado Potencial Hidroeléctrico)[4]. It aims to reduce the unused hydro power potential from 54% to 33% until 2020, installing new 2059 MW. This is expected to be achieved by two means: increasing installed power of already existing facilities (909 MW), and building ten new hydro power plants totaling 1150 MW of installed power. Among these projects, some include pumping capacity. The use of pumping allows more wind power to be installed: given that wind farms produce more in off-peak hours when electricity prices are lower, this energy can be used to pump water back to dams, so that hydro power can be generated during the hours of higher consumption and higher electricity prices. In 2007 the PNBEPH forecasted that in 2010 there would be 5100 MW of installed wind power, which contrasted with the 3751 MW achieved in reality. As a result, the completion of these plans are constrained by political and other factors (such as the fall of electricity consumption in 2010 and 2011). The future of the Portuguese power system remains uncertain, and in section 3.1 we explore some possible scenarios for 2020.

2. Impact Assessment and Logic Models

Impact Assessment aims at structuring and supporting the development of policies [5]. According to [6], ”impact” is often associated at the level of welfare of households and individuals. Impact evaluation presupposes there is both an institutional intervention (”impact of what?”) that produces results (”impact on what?”). These authors recognize that currently there is a shift in evaluation

[1]The yearly variation of hydro power production is reflected in the so-called ”hydraulicity factor”.

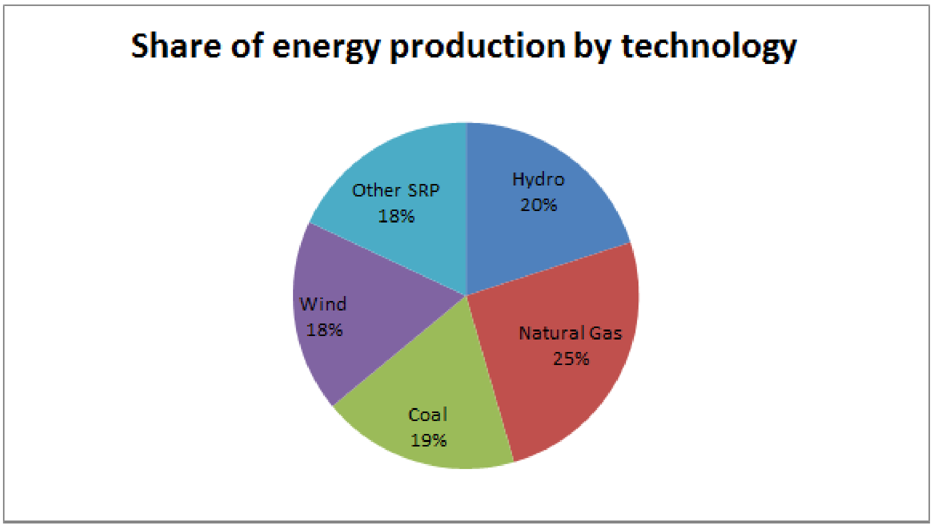

Figure 3: Electricity generation in Portugal, 2010. Own elaboration from www.ren.pt data. In order to present the numbers for a typical rainfall year, the numbers for hydro power were divided by the hidraulicity factor, which in 2010 was 1.31. The exceeding energy was assumed to be covered equally by coal and natural gas.

from small programs such as irrigation in a given district, to more complex intervention, induced by international treaties, such as the Kyoto Protocol [6].

Electricity production in the EU has become liberalized in the last decades. The role of the government as a central planner tends to be reduced and mostly previously state-owned companies and facilities tend to be privatized. Although under liberalization the government no longer oversees the entire planning process, the electricity sector decisions are still strongly driven by central authorities, addressing issues such as GHG emission limits, RES shares, external energy dependency or universal access to electricity. As a result, the market is not absolutely free and tends to be guided. So, to the questions "impact of what?" and "impact in what?", we may answer "impact of energy policy upon the standards of living of the population, having in the background the contribution of power systems to sustainable development".

Impact Assessment has been used widely within the EU and, in 2002, the single-sector assessment was replaced by a new integrated approach, capable of assessing economic, environmental and social effects [7]. This new approach allows Logic Models to be used when providing stakeholders with a visual map or narrative description of how specific program components are related to the program's desired results [8]. The literature related to logic models shows they have been applied both in a vast array of purposes, such as the monitoring of national R&D programs [9] [10], or education programs [11] [12] among others. For an overview of applications see the already mentioned [6].

The objective of this research is to organize the perceived short, medium and long-term impacts of electricity generation technologies, with the ultimate goal of assessing the sustainability of the Portuguese power system and supporting future strategic decisions in the electricity sector. For that purpose, logic models are built with the aid of both literature review and of interviews with a group of experts, as explained in the remainder of this section.

2.1. Methodology

MacLaughin et al. [13] dedicated an article to the use of Logic Models for program performance evaluation, and described a five stages process to achieve the Logic Model. The present work was conducted upon their instructions adapted to the topic under research:

1 - Collecting the relevant information: emphasizing the team work needed for building a Logic Model, along with the evidence that multiple perceptions about power planning exist,experts in power systems, with varied positions on key questions such as markets in general and the renewable energy sources' role were invited to enter the process. Documents used to build preliminary inference diagrams, were consulted, namely [14] and [15].

2 - Clearly defining the problem and its context: Here the assumption is that a problem, the power generation planning, is to be solved under resource constraints and framed on the European energy policies, as well as a globalized competitive market. Therefore, the power planning has to allow the electricity demand to be met using three groups of solutions (thermal, renewable and nuclear), while addressing economic, environmental and social issues.

3 - Defining the elements of the logic model: Starting with three tables (one for each Logic Model) with Resources, Activities, Outputs and Outcomes, the interviewees were induced to speak about implications brought by the building of each type of power plants, and fill the table, while seeking to describe short, medium and long term outcomes.

4 - Drawing the Logic Models: Considering the literature review and results of the interviews, the logic models were built for each technology. The results are presented further in the next section.

5 - Verifying the Logic Models with stakeholders: The logic models were presented to all participants in interviews to validate the results.

2.1.1. Conducting the interviews

The interviews lasted an average 45 minutes. The interviewees were firstly presented an example of a logic model to become familiarized with the goals of the interview. The chosen example was an European strategy to help reduce poverty, in order to avoid biases about sustainable development and energy; then the participants were invited to talk about economic, environmental and social impacts associated to each group of technologies, starting from the long-term perspective (example: how do you think that environment will get better if these technologies are used?) and progressing from there to more immediate impacts (which impacts does the construction of this type of power plants immediately cause?) While the interviewee was talking, the interviewer was filling the table with short, medium and long-term impacts and would then present it to the interviewee. The interviewer prepared, before the final results, a simple logic diagram and tables, aiming to discuss them further with the interviewee and possibly fill more impacts and connections that have arisen in the process.

2.2. Impact Chains

Based on the literature review and the interviews conducted with experts, three logic models were drawn (Figures 4, 5 and 6), presenting the impacts of electricity generation technologies.

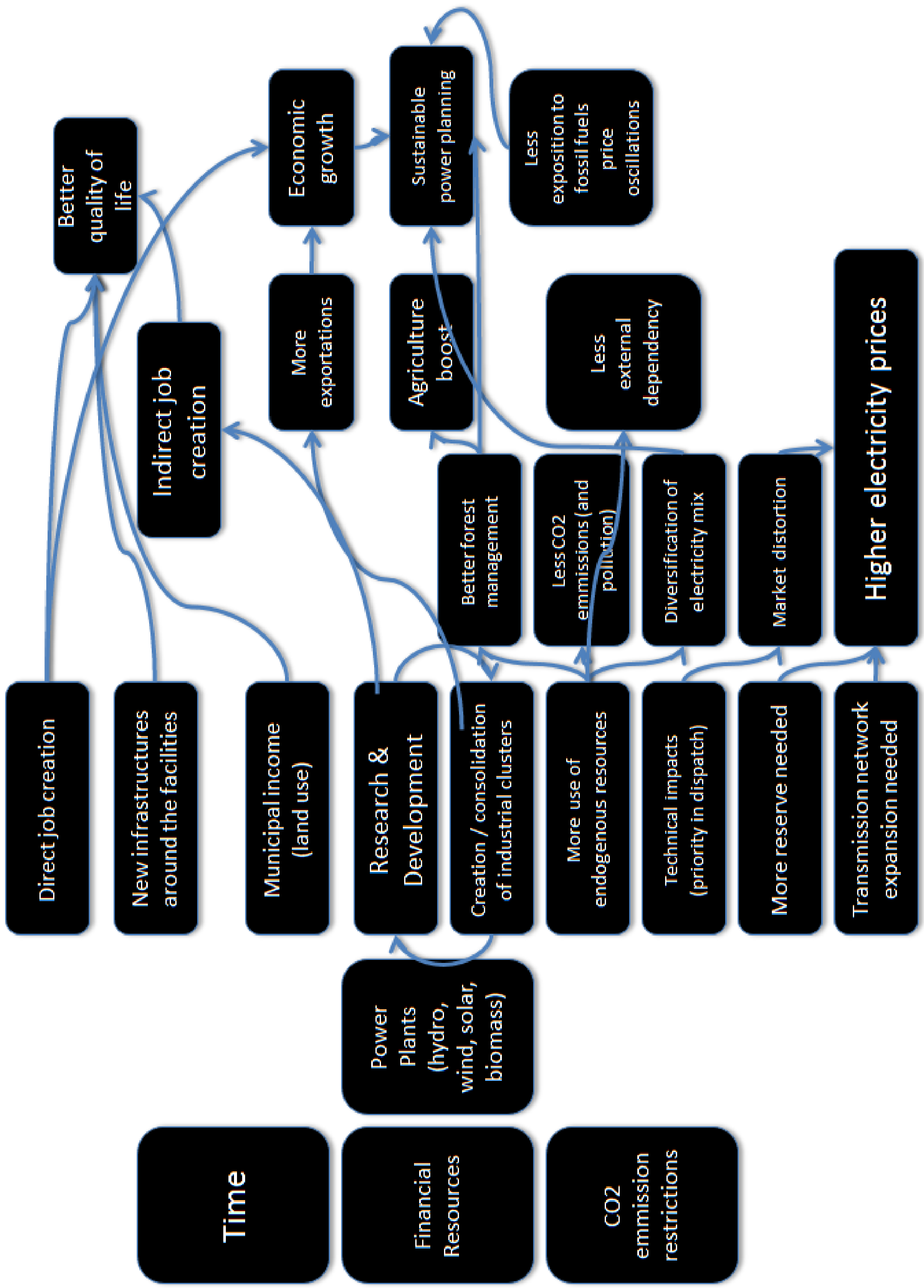

Figure 4: The Renewable Energy impact chain

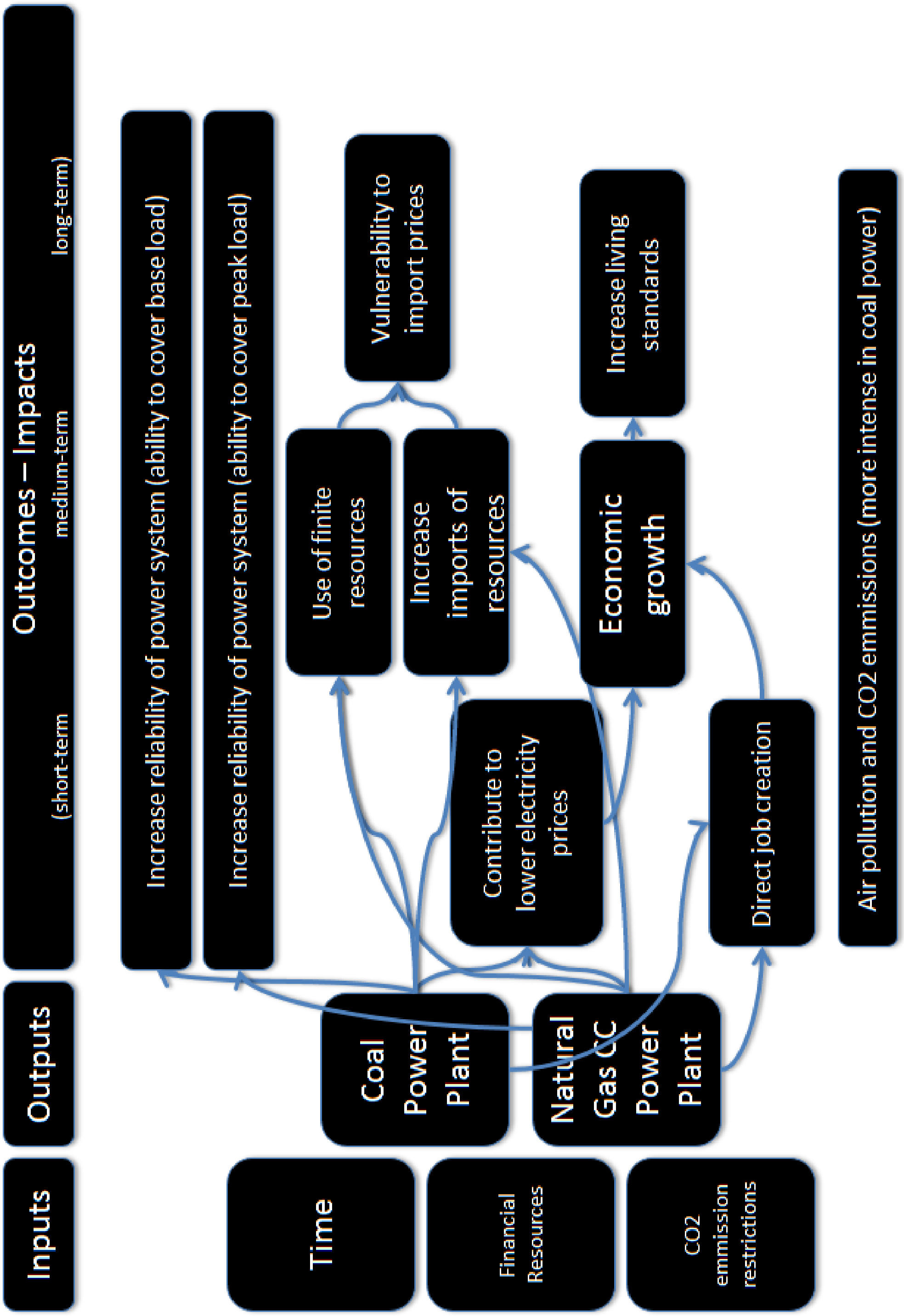

Figure 5: The Thermal Power impact chain

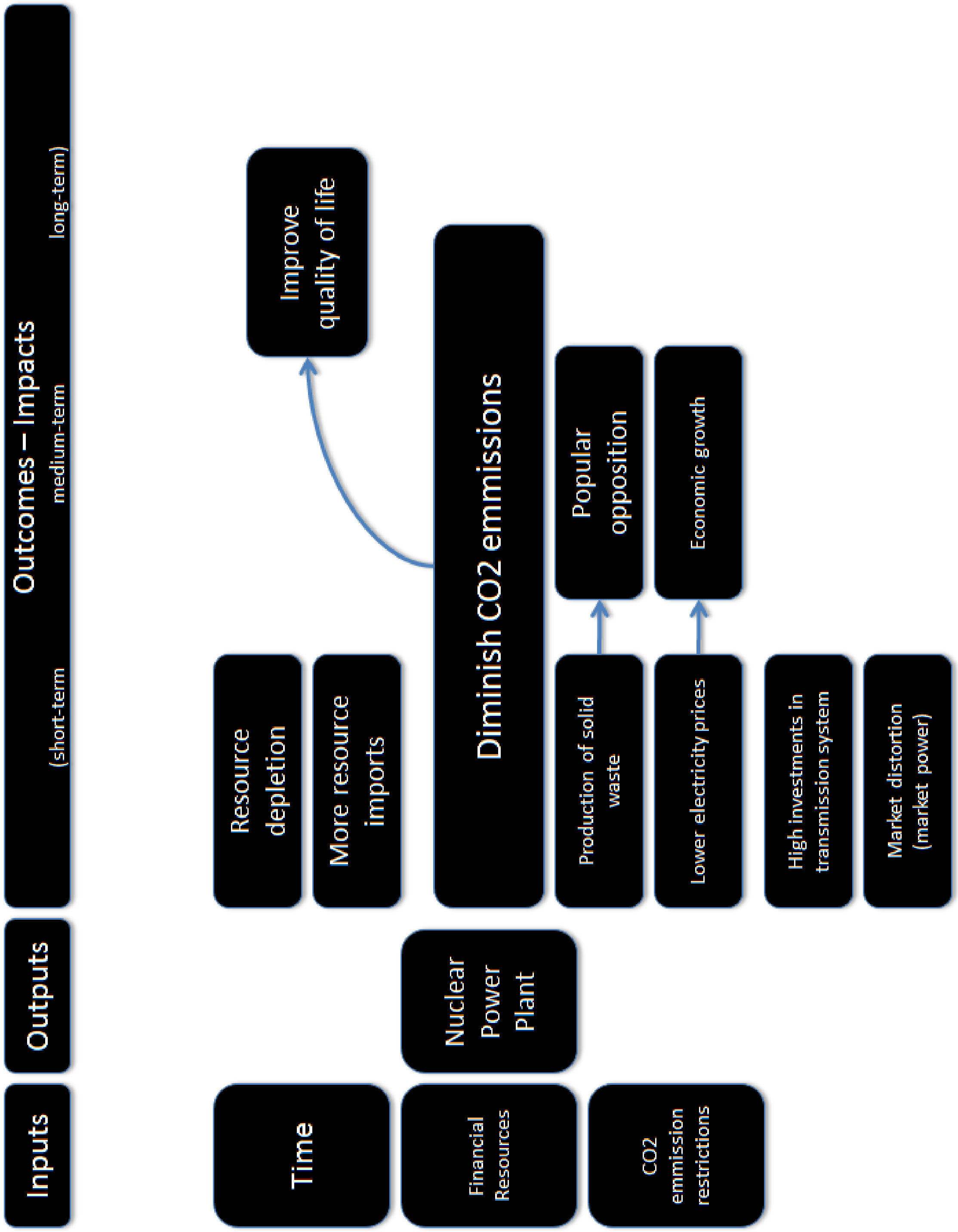

Figure 6: The Nuclear Energy impact chain

2.3. Discussion

Decision-makers with different political points of view will tend to favour different political aspects of strategies about energy. The most visible example is the position towards market prices in short-term. As electricity costs affect a wide number of commodities, it can be argued that it is essential for a country to provide cheap electricity. Otherwise the country will lose competitiveness, and eventually impoverish by losing industry and other economic sectors. This argument tends to transform the perspective on sustainability concerns (for example, poorer countries have traditionally been committed to fewer goals of emissions than developed ones). On the other hand there is the external energy independency factor, which can be achieved in the long run, and would be difficult to achieve yet in a free-market environment, given the high initial costs of exploiting the renewables. This duality is of extreme importance, and reflects what was said above: cost issues tend to prevail over social or environmental ones. The remainder of the discussion will reflect topics that have arisen in the interviews.

2.3.1. Renewables

One thing that became obvious during the process was that the renewables' logic model would definitely be more complex than thermal or nuclear power ones. Put simply, coal, natural gas and nuclear would be rational choices from a cost short and medium term perspective, while the renewables, being perceived as more expensive for now, have means to induce welfare in the long run.

The new infrastructures built around power plants were not seen as very important, given the fact that when they refer to roads, are normally away from large populated areas, therefore not resulting very useful. Other example of infrastructures built as a consequence of a dam is new housing due to population displacement, and this generally causes displease. However, one of the interviewees referred that new housing ends up causing more employment. Additionally, new infrastructures associated to renewables frequently disturb areas that used to be isolated, often spoiling landscape and causing visual intromission.

General agreement was achieved on the connection between knowledge (R&D), industrial clusters and energetic / economic independence. Interviewees agree over the misuse of the term ”cluster” as it is frequently assigned to wind power today. According to the general view, all the patents and most engineering aspects are imported. Instead a wider ”national” value-chain should be favoured which would definitely induce a more durable economic development.

Although general agreement is that employment creation favours renewables, some interviewees emphasized that job quality and duration have to be addressed, and that renewables' projects are often creating low duration and low qualification jobs. Even the creation of jobs was seen by one interviewee as a critical point, since he argued that job creation in renewables is still artificial and destroys jobs in more productive sectors of industry, given the still high costs these technologies represent.

Biomass is not believed to occupy a central place in the near future energy landscape (and only assuming the form of cogeneration), although it can help to manage the forest in a better way.

It is widely agreed that renewables, due to their intermittency, oblige the existence of traditional units (reserve/back-up). This contributes to turning RES electricity even more expensive as a whole. One interviewee mentioned the fact that the existence of wind power capacity installed in Portugal already produces excessive energy in off-peak hours, resulting frequently in energy exported for free in those hours.

Although there is an agreement that the increment of renewables' use induces less exposition to fuel fossil prices, this strategy can be discussed in the terms given above: is it worth to invest now or later? If later, when? How long will the natural gas and coal remain cheap?

Construction of transmission lines is a very important requisite to the construction of renewable energy facilities. RES development implies the decentralization of the grid, resulting therefore in a greater number of associated infrastructures, namely substations and transmission lines.

About the topic ”quality of life improvement”, it can be two-folded: general population improvement or more local improvement. It is agreed that renewables offer more local positive impacts; given the low density of installed power, many wind farms are equivalent to one gas power plant, for example; therefore, many rents will come from land use probably in different regions in the case of wind farms, benefiting more people. On the other hand, the rising prices of numerous commodities, given their relation to electricity prices, can be seen as negative.

2.3.2. Thermal Power

These technologies represent the status quo of power production, therefore contribute to keep low electricity prices at the cost of foreign dependency and vulnerability to finite resources price volatility. On the other hand, they represent tested and reliable forms of producing power. Coal is seen as a natural polluter in the long run, whereas natural gas is seen as cleaner from this point of view (a noble fossil fuel, in the opinion of two interviewees, which should not be burnt to produce electricity). The prices of natural gas depend very much on the regulatory framework and how will the Portuguese and Spanish markets evolve in the future and on decisive strategic investments in this area. Also, the ability of natural gas combined cycle power plants to contribute to lower electricity prices was stated to depend on the ability to integrate those with wind power. If natural gas power plants play a minor role, their production will cover only the few peak (expensive) hours. This can lead to the misuse of these power plants, turning hard to justify such large investments. Therefore, no linear or clear relation exists between the power plant and low output price, but it rather depends on how the power plant is used.

2.3.3. Nuclear Power

To what concerns nuclear power plants, it is agreed that only a large (in relation to the scale of Portugal) power plant is feasible, what would not only imply a redesign of the transmission grid, but also induce market power problems that would have to be carefully studied by regulators. The vulnerability to resource prices is not seen as dangerous as in the cases of coal or natural gas, given the historical stability of prices and its low value. This contrasts with the main problem: the high initial costs. Additionally, no know-how about nuclear power exists in Portugal, therefore knowledge and capital requirements have to account in the importations balance. Solid waste and opposition to power plants are very important matters yet, only expected to disappear if mankind manages to develop nuclear fusion technology and replace the traditional nuclear power plants.

3. Multi-Criteria Decision and Analysis Tool

3.1. Scenario Generation

In this section, the Scenario Generation phase of the methodology described in Figure 1 is addressed. In short, a Mixed Integer Linear Programming (MILP) model, running in GAMS (General Algebraic Modeling System) programming language is used. The input data for the model is given in an Excel file, as well as the solutions. For the detailed description of the optimization model, see [16]. The source code was used to create scenarios with different characteristics, based on the cost optimization of the electricity system. These scenarios represent different possible futures for the Portuguese power generation system in a 10 year range, departing from the present characteristics of the system and assuming the evolution of non-wind SRP forecasted by [15].

In table 1, five possible scenarios of electricity generation in the year 2020 are presented, aiming to represent five different strategies: investment in natural gas, investment in coal, investment in a mix of hydro and gas, investment in a mix of hydro and wind, and a moderated scenario following a business-as-usual approach. Obviously, none of these scenarios is likely to happen in this exact form due to the infinity of possible and distinct combinations, but, given the present state of the Portuguese electricity system, these are five possible strategies representative of different energy policy trends. The evaluation of more scenarios demands additional input information and higher response time on the MCDA tool. In order to ensure the effective participation of experts it was decided to keep the number of scenarios low.

Since the objective function is the minimization of the costs, constraints are used to diversify the scenarios. These constraints are of two types: allowing the program to install or not power plants of a specific technology, and, on the other hand, a renewable energy quota (sum of hydro, wind, biomass, photovoltaics and wave power) to be met in 2020. Not using these constraints would result in the model covering the demand with coal power, the least costly solution.

The "Coal" scenario is the least costly one, but also leads to highest external energy dependency (that is, highest share of coal and natural gas) and presents the highest CO_2 emissions. The other extreme case, presenting lowest external energy dependency and less CO_2 emissions is the "Maximum Renewable" scenario, with costs about 11% higher than the "Coal" scenario.

3.2. Scenario Evaluation Using the Multi-Criteria Decision Analysis Tool

The MCDA tool[2] is an Excel worksheet that aims to rank the suitability of electricity production scenarios according to 13 criteria. In the remainder of this section, firstly the methodology is exposed, then the MCDA tool is presented and finally applied to a case study, using the five scenarios presented in the previous section.

3.2.1. Methodology

A vast literature for MCDA applications to energy planning exists (see for example [17] and [18] for an overview). The proposed methodology could be summarized as direct weighting with an additive value function for amalgamation. As a result, it involves three phases, already mentioned in Figure 1: Impact Evaluation, Direct Weighting and Trade-off Analysis.

Impact Evaluation is the phase where a score, $score_{s,c}$ is assigned to each scenario s and criteria c. These values are then normalized, using a linear function $v_{s,c}$, so that the best values become 1 and the worst values become 0.

The user then assigns directly weights w_c to each criteria c. Finally, for every criteria c, trade-offs are presented in terms of costs, while the user is still able to change weights according to his perceptions.

[2] The tool is available for download in http://sepp.dps.uminho.pt/.

Table 1: Characterization of scenarios

	Constraints		Results			
Scenario	**Minimum Renewable Quota**	**New installed technologies**	**New installed power**	**Cost (euro per MWh)**	**Emissions (CO2 ton per GWh)**	**External energy Dependency**
Base	45%	All technologies allowed	700MW coal, 1000MW hydro, 4400MW wind, 1180MW other SRP (all SRP excluding wind power)	25.69	262	30%
Natural Gas	Turned off	Only CCGT allowed	2350MW natural gas, 1180MW other SRP	25.24	294	53%
Coal	Turned off	Turned off	2550MW coal, 1180MW other SRP	23.75	360	55%
Hydro-Gas	45%	Only CCGT and hydro power allowed	2050MW natural gas, 2000MW hydro, 1180MW other SRP	25.96	286	45%
Maximum Renewable	70%	No coal or CCGT allowed	2000MW hydro, 4400MW wind, 1180MW other SRP	26.37	250	28%

The final value for the scenario s is calculated according to the Additive Value Function (AVF), as follows:

$$AVF_s = \sum w_{c_i} \times v_{s,c_i} \tag{1}$$

where the higher the value, the better the solution is.

A brief example is now presented to illustrate the calculation of a trade-off: consider, from the above scenarios, that the user is weighting only two criteria: costs and external dependency. Taking into account that "Coal" presents least cost and highest energy dependency, the opposite case of "Maximum Renewable", the normalization of these criteria would consist in $v_{coal,cost}$=1, $v_{max\_renew,cost}$=0, $v_{coal,dependency}$=0, $v_{max\_renew,dependency}$=1.

As can be seen in Table 2, if only two criteria are weighted and the user gives the same importance to the costs and the energy dependency, he assumes implicitly that it is for him indifferent to choose scenario "Coal" or "Maximum Renewable". Here the notion of trade-off appears: for the user, the energy dependency of the "Maximum Renewable" scenario is worth 2,62 euro/MWh, which is the difference in cost between the scenario "Maximum Renewable" and "Coal" (26,37 minus 23,75). The calculation of the trade-off $T_{s,c}$ is performed according to the following equation:

$$T_{s,c} = \frac{w_c}{w_{cost}} \times score_{s,c} \times (26,37 - 23,75) \tag{2}$$

Since $T_{s,c}$ is already multiplied by the range of the price (the parcel on the right), its value is given in euro/MWh. The user is always given the % of the costs that this increment represents in relation of the coal solution cost: in the case of the example where costs and dependency have the same weight, T=2,62 euro/MWh and 2,62/23,75 equals 11,01%.

It is worthy observing that when the weight of the cost is equal to the weight of the external energy dependency, the scenario with best performance is the "Base", with AVF=94,79.

Table 2: Calculation of additive value function (AVF) by weighting two criteria

	Scenario s				
Criteria c	**Base**	**Natural Gas**	**Coal**	**Hydro-Gas**	**Maximum Renewable**
$score_{s,cost}$	25,69	25,24	23,75	25,96	26,37
$v_{s,cost}$	0,26	0,43	1	0,15	0
$score_{s,dependency}$	30%	53%	55%	47%	28%
$v_{s,edependency}$	0,93	0,07	0	0,3	1
	w_{cost}=$w_{dependency}$=**80**				
AVF_s	94,79	40,47	**80**	36,09	**80**
	w_{cost}=**100**, $w_{dependency}$=**50**				
AVF_s	72,19	46,88	100	30,30	50
	w_{cost}=**40**, $w_{dependency}$=**80**				
AVF_s	84,43	23,20	40	29,90	80

In case the user gives the costs a weight twice the external energy dependency, he would value the energy dependency in 1,31 euro/MWh (or 5,5%) and in this case the "Coal" scenario performs better than any other.

3.2.2. The MCDA tool

The proposed MCDA tool is presented in an Excel Workbook with five Sheets, as follows:

1. **General Instructions** The purpose of the tool is presented, as well as a summary of each of the following pages.

2. **Scenarios** The scenarios are presented graphically, detailing installed power and produced electricity for each technology. Energy dependency ratio, CO2 emissions and annualized costs are also displayed graphically.

3. **Instructions** Instructions for the following sheet are presented, along with an example.

4. **Impact Evaluation and Weighting** Here the user is presented with the 13 criteria, along with explanations of every one of them. The user then fills the required cells, according to what he percepts will be the impacts of each scenario. Trade-offs are presented.

5. **Results** Results are printed: both ranking of scenarios and contribution of each criterion is given.

In the remainder of this section the information presented and required from the user on the sheet *Impact Evaluation and Weighting* is introduced.

The criteria, C_i, and their description, are given as follows in Table 3. Since not all the impacts can be easily agreed upon, it was decided that the user might play a role on valuing them, as detailed in the column "Scenario score $i_{s,c}$".

Information of investment, operation & maintenance of the whole group of power plants is included in a single cost criterion. Positive impacts in industry, job creation and dependency on foreign fossil fuels have been an international concern for sustainable energy decisions [18] [17] with implications at national level [15]. Diversification of the electricity mix is also seen as important for sustainability goals [19] contributing to the security of supply. Local income, visual and noise impacts, as well as land use and public health were identified as important issues for local populations' standards of living, by the authors [3]. It is sometimes argued that the intermittency of the renewables imply they are overrated in levelized costs [20]: therefore, a criteria which accounts for the dispatchable rate of power on each solution was included. According to [21], the transmission system expansion requirements may be larger when renewable energy shares are higher; as the scenarios vary respecting to that aspect, the criteria was proposed to be evaluated. Given the importance that CO_2 emissions play in the economy nowadays, this criterion was also included.

Table 3: Description of the criteria used in the MCDA

C_i	**Name**	**Description**	**Scenario score** $i_{s,c}$
C_1	Costs	Sum of fixed and variable costs, divided by the total electricity produced during the planning period. The fixed costs are related with the investment cost applied to the new power plants and also with all fixed O&M costs. The variable costs include fuel and variable O&M costs for new and previously installed power plants.	Values in €/MWh, obtained from the MILP model. *User can not change values.*
C_2	National Industry	Impact of the scenario on the dynamics of the national industry.	Score in ordinal scale, ranging from 1 (worst) to 5 (best). *Requires user to attribute values according to own perception.*
C_3	Energy Dependency	Rate of dependency on foreign sources in year 2020, calculated as the sum of energy produced in thermal power plants (coal, natural gas and non-renewable cogeneration) divided by the total energy amount produced.	Values in %, obtained from the MILP model. *User can not change values.*
C_4	Employment	Employment created by the construction, operation and maintenance of the power plants.	Values are number of jobs. Obtained from the MILP model, based on [22]. *Although values are given, the user may attribute different values according to own perception.*
C_5	Visual Impact	Impact caused by the construction of new power plants upon the sightseeing.	Score in ordinal scale, ranging from 1 (worst) to 5 (best). *Requires user to attribute values according to own perception.*

C_6	Noise	Noise impact caused in neighbor areas by the new infra-structures.	Score in ordinal scale, ranging from 1 (worst) to 5 (best), based on [23]. *Although values are given, user may attribute values different according to own perception.*
C_7	Local Income	Rents originated by land use, for both public and private sectors.	Score in ordinal scale, ranging from 1 (worst) to 5 (best). *Requires user to attribute values according to own perception.*
C_8	Diversity of Mix	Diversity of installed power, calculated according to the Shannon-Wiener Index.	Higher values are better. Obtained from the MILP model, based on [24]. *User can not change values.*
C_9	Rate of Dispatchable Power	Ratio between the sum of installed power of coal, CCGT, dam hydro power plants, and all the installed power.	Score is given in %. Obtained from the MILP model. *User does not change values.*
C_{10}	Investment in Transmission Network	Additional investments required by the scenario. It was assumed that wind power has the worst impact, followed by hydro power, and no additional investment is required by natural gas and coal power plants.	Score in ordinal scale, ranging from 1 (worst) to 5 (best). *Although the values are given, the user may attribute different values according to own perception.*
C_{11}	CO_2 Emissions	Ratio between CO_2 emissions and the total electricity generated in the overall planning period.	Values are given in tons of CO_2 per GWh of electricity produced in the planning period. Obtained from the MILP model. *User can not change values.*
C_{12}	Land Use	Amount of land which becomes unusable by the scenario.	Values are given in 1000 km2, based on [22]. Obtained from the MILP model. *User can not change values.*
C_{13}	Public Health	Contamination of air, water, and general impact on public health.	Score is based on [23]. Obtained from the MILP model. *User can not change values.*

Figure 7 presents an example of the user's views of the MCDA tool for the C_2 criterion (National Industry). The scale for this criterion ranges from 1 (Low dynamics in industry) to 5 (Leadership of industry, resulting in capacity for exporting), and the user has assigned the following impacts for $I_{s,c}$: $I_{base,national\_industry}$=4, $I_{natural\_gas,national\_industry}$=2, $I_{coal,national\_industry}$=2, $I_{hydro-gas,national\_industry}$=3, $I_{maximum\_renewable,national\_industry}$=5. The blue cell is the weight of the criterion, assigned as 20 in the example. The information displayed in the plot indicates that the user accepts to increase the costs in 2.20%, in order to increase the national industry dynamics from score 2 to score 5. In other words, the user wishes to increase dynamics national industry from ”coal” or "national gas" levels, to the "maximum renewable" levels, and is willing to pay additional costs of 2.2% for that change. It is also implicit that the user is willing to pay more 1.47% to increase from score 2 to 4, and 0.73% to increase from 2 to 3.

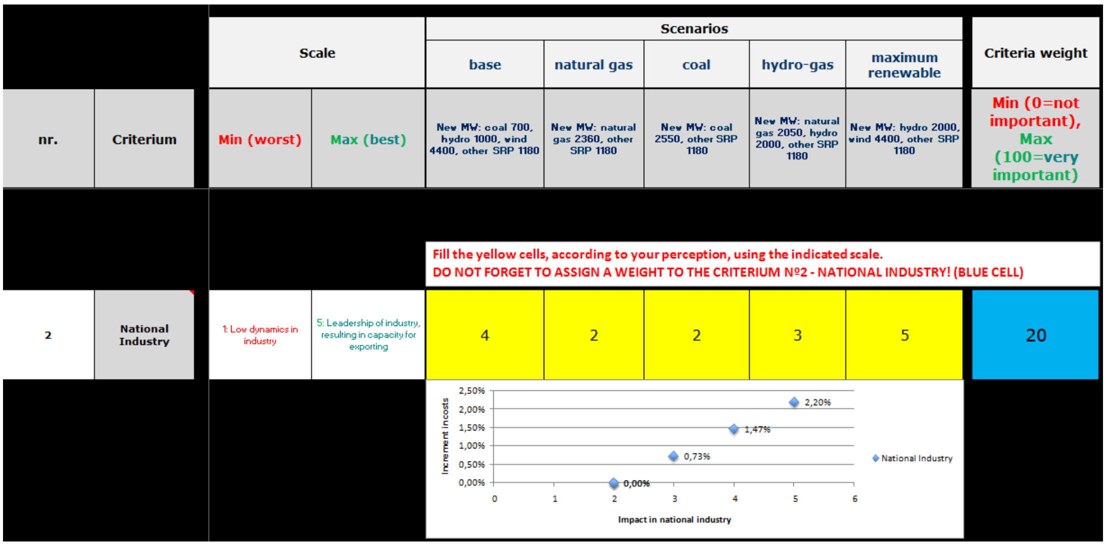

Figure 7: MCDA tool environment (Excel Sheet 4): Impacts and Criteria Weighting

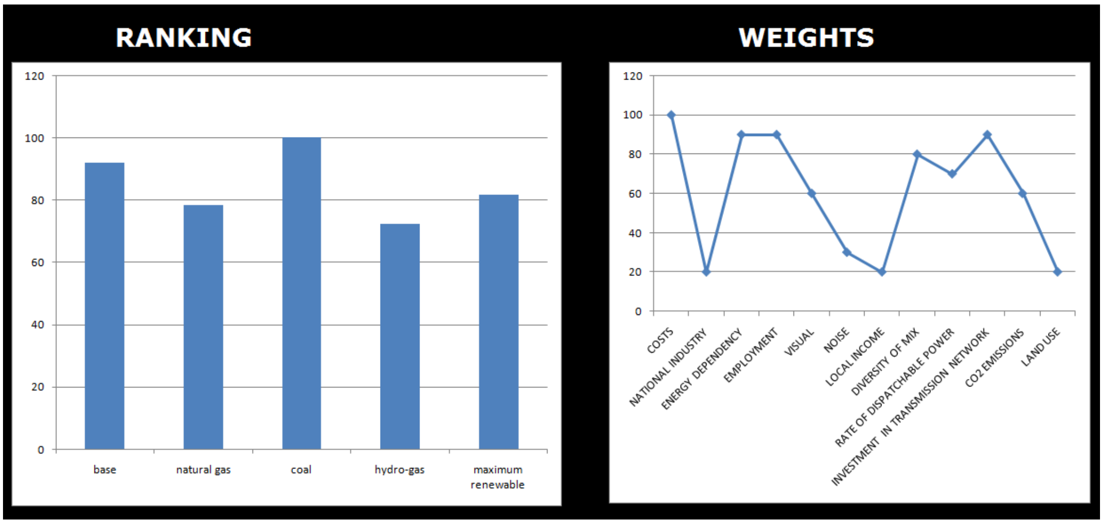

Figure 8: MCDA tool environment (Excel Sheet 5): Results. Here the user can validate his perceptions.

Finally, the *Results* sheet contains two plots, as can be seen on Figure 8: the one on the left, showing the overall ranking for the scenarios, and the one on the right showing the contribution of each criterion. The ranking is scaled so that the best scenario is scored by 100. On the given example, "coal" scenario is the most rated, while the "Cost" criterion is assigned as the most important.

3.3. Results

In this section the results are presented. The collaboration with academics took place in two phases. In the first place, the issues that should be included in power planning decision-making were collected with semi-structured interviews constructed over questions raised in the literature. The results of this exploratory research are described in section 2 of this report and published in [25]. In a second phase, the MCDA tool was sent by e-mail to approximately 60 academics, with background in energy, either from Economics or Engineering (Power Systems/Energy/Environment/Mechanical). The eleven experts that proceeded to the evaluation of the scenarios did it in a period of six weeks. Six of them responded to the tool by themselves, while the other five respondents were aided in a personal interview, which they found helpful and less time-consuming. Table 4 presents the weights assigned by each respondent to each criterion.

Table 4: Criteria weights.

	Respondents										
Criterion	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**
Costs	50	80	25	80	70	100	100	80	80	80	80
National Industry	30	20	50	50	20	25	37	30	25	30	100
Energy Dependency	30	70	70	70	50	100	0	30	35	20	100
Employment	30	60	60	50	50	50	37	75	35	20	100
Visual Impact	1	5	50	0	80	50	9	20	15	10	100
Noise	6	2	25	50	0	50	9	10	20	5	30
Local income	0	30	50	10	0	75	0	10	17	5	70
Diversity of Mix	15	20	60	20	80	100	15	10	12	20	70
Rate of Dispatchable Power	7	40	25	50	100	50	30	20	30	20	50
Investment in the Transmission Grid	15	20	25	10	0	75	18	30	35	5	50
CO_2 emissions	5	60	60	50	0	90	27	30	40	0	100
Land Use	0	5	40	20	20	75	5	60	15	5	20
Public Health	30	10	70	50	70	90	18	60	45	5	85

Figure 9 aggregates the results, that were normalized for each respondent, so that the highest weight equals 1 and the lowest equals 0. Costs prevailed as the most important criterion, followed by energy dependency, followed by two social concerns: public health and employment. Least important criteria were noise, visual impact, land use and local income.

The resulting rankings are presented in Table 5. There are no dominated solutions, which means that no scenario performs always worse than any other scenario.

Even in the cases that cost is regarded as the most important criterion, the best solution can either be the cheapest or the most expensive. Concrete examples of this situation were the case of respondents A and D, that placed costs weight higher than any other criterion, but also valuated other criterion high, and diluted the importance of costs.

The only scenario that never ranked first, for any respondent, was ”Hydro-Gas”. However, it is a balanced scenario, since it only ranks in the last place twice, while ”Maximum Renewable” and ”Natural Gas” rank in the last position for three respondents’ profiles. On the other hand, ”Base” is the only scenario that never ranked last place, although only ranks first in two respondents.

Figure 10 presents the contrast between respondents favorable to ”Coal” and ”Maximum Renewable” scenarios, showing that while the former group clearly places costs high above any other criteria, the

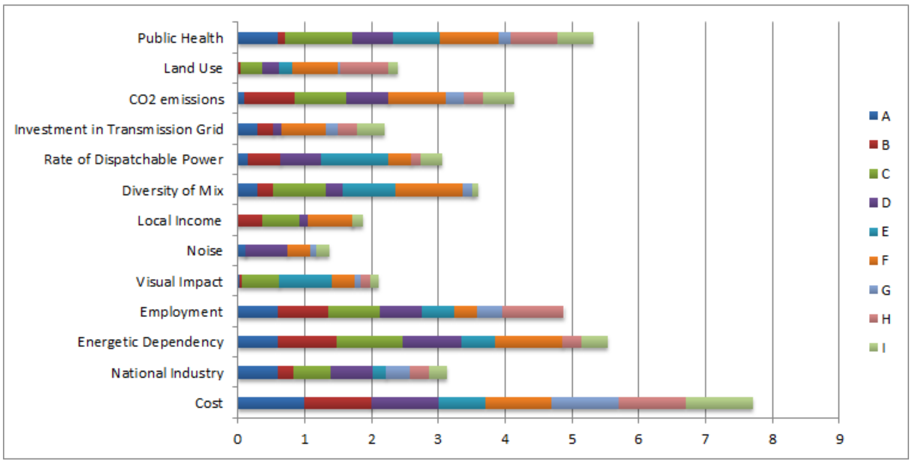

Figure 9: Aggregation of results

latter have five similarly valuated criteria: costs, public health, energy independency, national industry and employment.

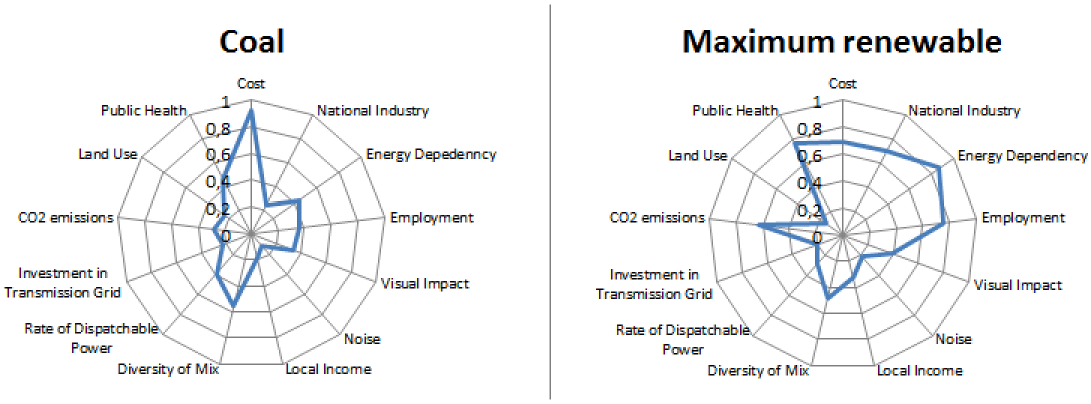

Figure 10: Average profile of respondents that chose either "Coal" or "Maximum Renewable" as preferred scenarios.

The resulting rankings are presented in Table 5. Coal and Maximum Renewable were the scenarios that ranked first more times (4 times each). Our results confirm that costs are the main obstacle for the incorporation of more renewable energy in electricity systems. Like the case of [26], our scenario ranking was also very sensitive to the input of costs weight.

What these results have shown is, in first place, that respondents felt it is important to trade-off costs with other criteria, hence the utility of multi-criteria methodologies. Only on rare occasions did a respondent assign zero to the weight of one criterion, but was free to do it in any criterion he wished to (if he assigned zero to all criteria besides costs, obviously the Coal scenario would be the first in the ranking, since it is the cheapest solution). Secondly, it is the magnitude of the trade-off that induces the divergence in the final rankings. For example, for the second most rated criterion, energy dependency, one respondent suggested that more information should be given when valuating this criterion ("in the worst case for fuel cost projections, how much would the cost of the solution increase?"), otherwise it becomes difficult to state how much would he be willing to see the solution costs increased. However, using more information would significantly increase the response time.

Table 5: Scenario Ranking.

	Respondents										
Scenario	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**
Base	2	**1**	3	2	4	2	3	**1**	4	2	2
Natural Gas	5	5	4	5	3	4	2	4	**1**	4	5
Coal	3	3	5	4	**1**	**1**	**1**	3	2	**1**	4
Hydro-Gas	4	4	2	3	2	5	4	5	3	3	3
Maximum Renewable	**1**	2	**1**	**1**	5	3	5	2	5	5	**1**

4. Conclusions

In section 2, a wide array of impacts was constructed from literature review and interviews with experts in power systems, and assumed the form of comprehensive impact chains or logic diagrams. These can aid decision-making in sustainability issues and evaluation applied to power systems. A contradiction still exists: between needed short term economic competitiveness and long term sustainability. This means that trade-offs must be considered for the definition of electricity strategies for the future. Although this is an assumption accepted in general, political factors tend to influence significantly the decisions, even surpassing the power systems expertise. This work was applied specifically to the Portuguese situation, but with minor changes may also be representative of other countries.

Given that the traditional sources are not limitless, RES will eventually have to play an important role in the future, when fossil fuels become more expensive. This will turn RES automatically attractive under an economic perspective. Before that time comes, RES are still expensive, but can foster knowledge, new industries and eventually economic growth, especially for countries like Portugal, which relies mainly on foreign resources.

Since the expert interviews show some scepticism about the RES job creation potential and even about the RES ability to improve locals quality of living, it turns essential to proceed to the second phase of the research, to talk with local stakeholders, in order to recognize their perceived negative and positive impacts. As for thermal power plants, the importance of local impacts does not seem to be as significant. The general view of experts clearly favours that national level impacts are the most important ones, turning the local impact assessment studies a less important requirement for the verification of the logic models. In fact, most of the impacts related to CO2 emissions, cost or volatility of fossil fuel prices may be evaluated resourcing to mathematical models such as Pereira et al [16].

In section 3, a tool to evaluate scenarios for electricity production was proposed. The tool uses multi-criteria decision analysis, and comprises a set of thirteen criteria, ranging from economic concerns, to environmental and social as well as technical issues. The methodology combines an additive value function that aggregates results from direct weighting and trade-off analysis. The proposed tool was used on the particular case of Portugal, based on a set of scenarios for the electric system in 2020. A group of experts from academia, Engineers, Economists related to the energy sector, participated in the evaluation of these scenarios. From the results obtained, most respondents would be willing to increase the costs of power generation if other issues than the economical ones were to be taken into account. This fact alone proves the utility of MCDA. The evaluated scenarios were ranked differently by respondents with different perspectives, what is not unexpected when using multi-criteria methodologies: like [27] pointed out, MCDA is useful in mapping different views without forcing initial consensus and may facilitate future negotiation. Only one of the scenarios, "Hydro-Gas", was not chosen to be the preferred by any of the eleven respondents.

Aggregating the results, cost was considered the most important criterion, even for most respondents whose preferred scenario was ”Maximum Renewable”. Other also important criteria were the rate of dependency on fuel sources, the employment and the public health issues. Depending on the weight assigned to these criteria, the cost loses relative importance and most expensive solutions may rank first.

In future work more results will be collected. The public acceptance of different technologies will also be evaluated.

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