Sustainable choice of the location of a biomass plant: an application in Tuscany

Filippo De Carlo [#1], Massimiliano M. Schiraldi [*2]

[#] Department of Industrial Engineering – University of Florence
Viale Giovan Battista Morgagni, 40 – 50134 Firenze - Italy
[1] filippo.decarlo@unifi.it
[*] Department of Enterprise Engineering – University of Rome at Tor Vergata
Via del Politecnico, 1 – 00133 Roma - Italy
[2] schiraldi@ing.uniroma2.it

Abstract— **The management of complex systems often requires taking decisions that may affect the company's future. Making decisions is not easy and requires you to take serious responsibility. The company character appointed to this task, is the "decision-makers" who, within a job or project, must make a selection among several alternatives. To carry out this task, you must perform a process called "decision analysis". It can be aided by qualitative and quantitative tools, able to rationalize a multifactorial choice and bring it to a judgment of performance parameters more easily comparable. In fact, if this problem is addressed considering only the economic aspects, other fundamental parameters will be neglected such as, for example, the environmental ones. Actually, bringing many different aspects to a simple economic performance, or anyway one-dimensional, proves to be a limiting and unsatisfactory approach. In addition, if we consider the concepts of sustainability, we should at least take into account the three dimensions that describe it, namely the economic, environmental and social issues. Then, a strategy of decision making more complete that could integrate all the three aspects, becomes much more appropriate. In this context, the multi-criteria analysis are particularly suitable for this purpose. In this study we aim at investigating how one of the most popular multi-criteria methods, the Analytic Network Process (ANP) can be used to define the location of a cogeneration plant fuelled by biomass. The novelty of this study consists of having categorized and divided into homogeneous areas an entire region. In addition, to evaluate the economic efficiency, as compared to other authoritative work on the subject, also the water content in the raw material was considered, influencing the amount of biomass consumed. The results show that the ANP allows decisions making according to an overall view, considering a wide variety of parameters and allows the decision makers to better represent the needs of the stakeholders**

Keyword- Sustainable development, Analytic Network Process, Energy economics, decision support system.

I. INTRODUCTION

The economic development and the technological progress lead to a continuous development of technologies and require a constant effort of renovation of existing facilities. On these occasions for renewal, you must face the serious problem of making an appropriate choice of the location of such new plants. This choice is influenced by many conflicting parameters.

Technical, economic and environmental needs, must be taken into account simultaneously. The experience of those who are required to make a choice (the decision-makers) teaches that it is unlikely to find a solution that simultaneously optimizes all aspects. Our society, in fact, is marked by the need to constantly find compromises that fully satisfy all stakeholders. In many cases, multiple decision-maker groups are involved in the judgments. Each group brings different viewpoints and priorities, which must be resolved within a framework of mutual understanding and mutual compromise.

The international scientific research has proposed tools to help decision-makers, which were developed starting from one-dimensional models [1], [2], [3]. A decision analysis based solely on economic considerations, however, turns out to be incomplete, as it is based on an outdated concept of development, understood only as economic growth: this, in itself, is not enough, but the development is real only if it improves the quality of life in a bearable manner [4]. The next change of these tools was marked by the introduction of multi-criteria decision making (MCDM) techniques. In recent years we have seen the development of many applications in various fields: from the integrated manufacturing systems [5], the evaluation of technology investments [6], water and agricultural resources management [7] [8] in addition to the energy planning [9] [10] [11].

The need to make decisions, taking into account multiple conflicting aspects, is real in all industrial sectors, and particularly in the energy sector [12] [13]. In this context, in fact, the need to reduce the environmental impact of power generation plants, requires a continuous decommissioning and new installation. The aspects to be taken into consideration are well summarized by the concept of "sustainable development", born since the

70s. Its most widely used definition is the one provided in 1987 by the World Commission on Environment and Development, chaired by Gro Harlem Brundtland, according to which: “Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs” [14].

Many other definitions of sustainability are based on three fundamental aspects: environmental protection, social responsibility and economic progress [15]. It follows, therefore, that the pursuit of sustainable development depends on the capacity of governance to ensure full interconnection between the economy, society and environment. The complex interactions between these three fundamental aspects, make decision-making difficult. For this reason, is often applied a MCDA approach [17] [18], which provides a way to making a decision [19], considering a wide range of parameters, even interdependent [20] [21] [22].

A topic of great interest for sustainable development, is related to the identification of the best location for biomass plants, which are highly technologically developed in recent years. These are divided into two main families: the installations that employ thermochemical processes and those that employ biochemical processes [23] [24] [25] [26]. The first can be divided into combustion, gasification and pyrolysis, while the latter are divided into fermentation and anaerobic digestion. The biomass gasification is a technology in great development, used for the production of energy. It has been widely studied in recent years by researchers and by manufacturers of energy production plants [27] [28] [29].

The gasification process is well known since the last century and up to now is used on a large scale within the refineries as a key technology to convert coal and petroleum residues into synthesis gas (syngas). The product from the gasification process is the syngas, a mixture of partially combusted gas and therefore susceptible to further oxidation (in an internal combustion engine fuelled by gas).

The gas forming the mixture are: H_2 (hydrogen) and CO (carbon monoxide) and, in small quantities, methane (CH_4). The cogeneration system allows to obtain a thermal recovery on three fronts: the cooling of the syngas, the cooling of the cogenerator and the hot fumes in output of the fireplace. Although the technology of gasification of woody biomass, does not have a great historical background and claims an excellent quality of wood chips at the input, it is quite common in small plants (less than 500 kWe). Bigger installations require a very careful feasibility study. The development of this technology is very rapid, and most recently, scientists are trying to overcome the obstacles to a wider use, such as gas cleaning and especially reducing the tar [30] [31] [32].

There are many studies in the literature in which MCDM techniques have been applied to the energy production plants. In particular, we can identify three main broad categories of approach: (i) the Value measurement models, (ii) the Goal, aspiration and reference level models and finally (iii) the Outranking models (also called the French school) [33]. The ANP technique, a development of AHP (Analytic Hierarchy Process) was introduced by Thomas Saaty [26], can be placed in the first of the above categories and was widely applied in studies of new energy systems development [34] [35] [36]. The current situation, therefore, presents both the availability of multi-criteria decision support tools and very refined technical-economic models for the determination of cost-effectiveness of biomass plants. One of the best is certainly that of Caputo et al. [37], later echoed by other researchers [38] [39], in which is proposed a methodology for evaluating the economic feasibility of biomass utilization for energy production by means of the gasification-conversion principle from 5 to 50 MW.

In this study, the method applied relies on the cost of each source, which is clearly estimated, as well as the power output thanks to specific conversion formulas. One possible development could be the inclusion, in the evaluation of the net power produced by the plant, of the lower calorific value of the consumed biomass as a function of its moisture content. This model enrichment might then converge into a MCDM able to compare different alternatives of location, qualified also according to the moisture content of the biomass present in each zone.

With this work we aim to bridge the gap of the absence of examples in the literature that demonstrate whether the AHP analysis is able to compare different alternatives of location of gasification plants, within a broader regional context. This must be done bearing in mind both the possible differences in interpretation of the concept of sustainable development, both the quality of the biomass expressed in terms of the type of raw material and its moisture content. Against this background, the aim of this study is also to evaluate whether the ANP can incorporate these issues and be a valuable support tool for decision makers. It must enable them to identify the best alternative among all possible ones, allowing them to properly model the typical aspects of sustainability, best interpreting the priority of a particular decision maker, be it a public administrator, an investor or an entire community.

The present work is based on a case study, specifically analysed, consisting in choosing the best location for a power plant fuelled by biomass from wood chips, in the whole region of Tuscany, Italy. The biomass was qualified both according to the type and on the moisture content. The assessment took into account very heterogeneous aspects, all classifiable in the broad concept of sustainable development. We considered the economic aspects, including the presence of regional and national incentives, the social and environmental aspects. The possible alternative scenarios were then evaluated, according to the different priorities that a particular decision-maker can have. The methodology proved to be very flexible and allowed us to clearly identify the preferential areas for the installation of these facilities. Even the modelling of the moisture content has allowed to improve the assessment, making them more reliable.

The remainder of the article is structured as follows: Section II exhibits a brief presentation of the AHP and ANP methodologies. Section III describes the case study and the main results. In Section IV, finally, there are both a discussion of the results and the final conclusions.

II. METHODS

MCDM indicates a large family of techniques that can simultaneously take into account a variety of aspects of the problem that you are facing. These features can be both quantitative and qualitative. The weight that the decision maker assigns to each criterion, makes the tool flexible, allowing you to bring out the different points of view of all the players involved [40] [41]. This paper exploits a MCDM approach and, in particular, the Analytic Network Process, a generalization of the Analytic Hierarchy Process, which is proved to be too restrictive in our case. For a thorough theoretical discussion, you can refer to the texts of Thomas Saaty listed in the bibliography [42],[43],[44],[45].

A. AHP

The AHP is a tool used to set priorities in a complex situation by the use of a hierarchical structure that represents just such a situation [46]. This approach was developed by the mathematician Thomas L. Saaty around the end of the seventies and is mainly divided into four stages:

1) hierarchical decomposition of the problem;
2) compared evaluations with pairwise comparison;
3) hierarchical consolidation and synthesis of priorities;
4) check of consistency.

1) First stage

In the first phase are identified: (*i*) the overall objective, (*ii*) the criteria for achieve this objective, (*iii*) any sub-criteria and (*iv*) the options from which carry out the decision. These elements are arranged in a tree or pyramidal hierarchy. Basic concepts in this regard are the dependence of the lower levels on higher ones and not vice versa, and the independence of each element within the same level.

2) Second stage

In the second phase, the technique of pairwise comparison is used, to establish priorities among the various elements of each level of the hierarchy, that is the elements of a level are compared, two by two, with respect to each element of the upper level. In this way, the criteria are compared with each other in reference to the general objective, the sub-criteria in reference to the relative criterion and, finally, the alternatives with respect to the sub-criteria. Comparisons between the elements are made using the Saaty semantic scale, which allows to transform qualitative judgments in numbers, as shown in Table I.

TABLE I
Saaty semantic scale. The table show how to transform qualitative judgments into quantitative data.

Intensity of importance	Definition	Explanation
1	Equal important	The two elements contribute in equal manner to achieve the objective
3	Weak importance	The judgment is slightly in favour of an element
5	Strong importance	The judgment is strongly in favour of an element
7	Very strong importance	The predominance of the element is amply demonstrated
9	Absolute importance	The evidence in favour of an element is of the maximum order
2,4,6,8	Intermediate values	When compromise is needed

This yields the dominance coefficient, which represents the dominance of one element on the other with which it is compared. If the i element has a certain dominance coefficient compared to the element j, the element j will have, as dominance coefficient, the mutual of the previous.

All the dominance coefficients Obtained from the pairwise comparisons, are joined in a square matrix, the matrix of pairwise comparisons, structured as in equation (1), where a_{ij} is the dominance coefficient of i with respect to j:

$$A = \begin{vmatrix} a_{11} & a_{21} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \dots & \dots & \dots & \dots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{vmatrix} \quad (1)$$

3) Third stage

In the third phase, the priorities among the elements of each array are deduced, from the values within the pairwise comparisons matrix, therefore obtaining a scale of values that expresses the final preference of the alternatives, compared with respect to the benchmark criterion. To obtain global priorities, that is, to obtain a total ordering of alternatives in relation to the final objective, you must proceed for aggregation and comparison of criteria set on the upper levels. The global order, therefore, is obtained by the weighted sum of the vectors of local priorities, or rather performing the weighted sum of the scores given to each alternative (indicating the degree of preference of one over another), and the weights assigned to the criteria and sub-criteria.

Once obtained the global weights, we will have obtained the results of the analysis: the greater is the total weight of an alternative, the more advisable it will be.

4) Fourth stage

The fourth step involves the verification of the consistency of the matrix, that is we need to try its reliability, since the human aptitude may meet some difficulties in establishing the relationships between the different elements. In such a case, there could be problems in maintaining the consistency of judgment in all pairwise comparisons.

Because the matrix can be defined consistent, the consistency ratio (CR, see equation 2) must be below 10%:

$$CR = \frac{CI}{RI} \quad (2)$$

In the previous expression, CI is the consistency index, calculated according to the rank of the matrix and to the value of the principal eigenvalue. RI, the random index, is a parameter whose values are calculated experimentally, and vary with the rank of the matrix..

AHP is an excellent decision analysis tool when applied to situations that can be modelled as a hierarchy of levels, inside of which there is independence among the elements of the same level and among those of the higher compared to those of the lower levels. The hierarchy implies a one-way process, going from top to bottom, without allowing to climb the chain of decision-making.

A network, unlike a hierarchy, is spread in all directions and does not require the independence among the elements: this allows to create models much more similar to reality, as, very often, the different aspects considered for the determination of the best choice are, by nature, dependent on each other.

In our case study there is no independence among the various criteria taken into account, therefore the use AHP would excessively distort the final result of the decision-making analysis. Precisely for this reason, we chose to use a more interconnected approach with a network.

B. ANP

In ANP the decision problem is therefore structured as a network of elements organized into groups, according to multiple relationships of influence. The development of the ANP is based mainly on four phases:

1) development of the structure of the decision-making process;
2) compared evaluations with pairwise comparison;
3) construction of the supermatrix and aggregation of the results;
4) sensitivity analysis.

1) First stage

In the first phase, the goal to which the analysis should lead is set. Then you must break down the decision problem into groups of elements and alternatives to choose from. The network structure is, in fact, represented by a set of components (or clusters) within which are contained the elements (or nodes). The connections between the different clusters and elements shall also be made.

2) Second stage

The second stage develops in the same way of the pairwise comparison of AHP method: it expresses a preference by the creation of multiple pairwise comparisons between all the elements connected to each network element. In the ANP, however, comparisons are also made between the clusters.

3) Third stage

In step 3 the results from the pairwise comparison are integrated. This happens through the gradual formation of three supermatrixes: (*i*) unweighted (or initial) supermatrix; (*ii*) weighted supermatrix; (*iii*) limit supermatrix. The unweighted supermatrix

The unweighted supermatrix is composed of the priority vectors (x) obtained from the pairwise comparison, held using the same methodology of the AHP.

The weighted supermatrix differs from the previous one, because it takes into account the weights assigned to each cluster: by multiplying the values of the initial supermatrix for the matrix obtained from the comparison between the clusters, we obtain the values of the weighted supermatrix

The limit supermatrix is the matrix whose columns contain the vector of the priorities of the elements in analysis. This is obtained by multiplying the weighted supermatrix for itself a number of times approaching infinity. After determining the values of this supermatrix, you get global priorities, which are the target of the analysis.

4) Fourth stage

In the fourth phase, you go to check the stability of the final ranking of preferences, varying the weights assigned to the control criteria. Therefore, you can evaluate the robustness of the decision model.

In particular, as regards the ANP, the sensitivity analysis allows to consider, from time to time, a criterion of control as an independent variable and then observe how the final ranking of the alternatives changes by varying the weight assigned to such criterion.

III. RESULTS

A. The case study

This paper focuses on determining the best location [45] for a biomass plant, within Tuscany region, in Italy. The choice should be based on the principle of sustainable development, so the purely economic analysis which is usually carried out initially, was considered to be unduly limited: thus the ANP method was applied to the present case study.

Fig. 1. Tuscany map. In the picture is shown how we divided the region into homogeneous areas.

The plant in question is a generic biomass plant with the following characteristics

- Type: Integrated Gasification Combined (IGCC), that is a combined cycle made of a gas turbine and a steam plant, powered by gasification of solid fuels (biomass in our case).
- Size of the plant: between 5 and 50 MW.

The size strongly influences the volume of biomass consumed, which is connected to the main logistics costs of collection, transport and storage [47].

- Considered biomass: wood chips. It 'a kind of biomass fairly inexpensive and readily available on the regional market.

- Type of gasification unit: “fluid bed” kind, which is commercially developed in the range between 5 and 300 MW. This should a pressurized type (with a variable pressure between 5 and 50 bar) to benefit from the advantages associated with it. The carrier gas used is air.
- Pre-combustion preventive filtering, in order to limit the cost of such a phase, including a section of hot gas filtration from ash particles of coal dust.

The possible alternatives for the location of the plant are the four macro-areas in which we divided Tuscany, and called North, East, South and West, as shown in Figure 1.

Obviously these four areas do not correspond exactly to a division based on the cardinal points, but are areas as homogeneous as possible with each other for territorial structure, the presence of biomass, topography, government and so on.

Each zone is characterized by two essential parameters: the amount of total available biomass residues and their origin. In fact they have different characteristics in terms of anhydrous calorific value and percentage of ash, depending on whether they are forest residues, agricultural, or resulting from the wood industry. Two other distinguishing parameters that vary from area to area are the purchase price of wood chips and percentage water content, which will prove to be the most significant parameter in the decision-making process.

The average values for each area of Tuscany, were obtained by analysing the types and origin of the wood chips in the different zones. A summary of the collected data is given in Table II:

TABLE II
Average characteristics of the wood chips in the four areas of Tuscany. The features that vary from area to area are the anhydrous calorific value of wood chips, the percentage of water content, the percentage of ash produced by the combustion of wood chips and the cost of.

Area	**Anhydrous Calorific Value [MJ/Kg]**	**Water content [%]**	**Ash [%]**	**Cost of biomass [€]**
North	19.1	45%	1.90%	40
East	19.2	40%	2.10%	45
South	19.4	30%	2.30%	55
West	19.3	35%	2.06%	50

As visible in Table I, the Anhydrous Calorific Value and the percentage of water content, are better in the South area, while as regards the percentage of ash produced and the cost of biomass, the North is better.

A further distinctive parameter for each area, it is the amount of biomass available from dedicated energy crops: the ability to create this kind of crops is closely linked to the possibility of generating employment and then welfare to society. This possibility appears to be higher in the North, followed by East, South and West. All data were derived by referring to the sources listed in the bibliography: [48], [49], [50], [51], [52].

B. Economic analysis:

We performed a preliminary economic analysis, modelling the plant through a transfer function defined as the ratio between a generic output and a generic input. In our case the function transforms the biomass weight M into a net electrical energy power output (W_{NE}), making the product of the plant energy conversion efficiency (η_e) for the biomass low heating value (LHV) and dividing it by the operating hours (OH), as shown in equation 3.

$$W_{NE} = \frac{M \cdot \eta_e(W_{NE}) \cdot LHV}{3{,}6 \cdot OH} \qquad (3)$$

It is worth noting that the efficiency depends on the energy power output, making eq. 3 an implicit equation.

After defining the three parameters that characterize the transfer function, η_e, LHV and OH, we got an approximation of the function that allows to calculate the amount of wood chips consumed as a function of the plant size, for each of the four zones. It will be shown that the most incisive element is the percentage water content, which is innovative if compared to the reference model [37].

One of the objectives of this first phase, was the approximate calculation of the Net Present Value (NPV) of the system considered, as a function of its size (between 5 and 50 MW). To do this, it was necessary to clarify the investment costs (IC) for the machinery and their installation, and the annual operating costs (OC).

Subsequently, in order to get the goodness of the investment, the relationship between the costs and the net power was obtained, so as to express the NPV as a function of the latter, for each of the four alternatives. For the calculation, we relied on the values used in the sources [37], [53], [54], [55]. For each of the four alternatives, we got two NPV functions: one in case the selling price of electricity is not incentivized and one, instead, considering incentives obtained with the feed-in tariff which replaced the green certificates.

C. MCDM approach

In the economic analysis just presented, only the economic parameters have been taken into account, while the purpose of the multi-criteria analysis is to find the best alternative, making a sustainable choice, considering the economic, environmental and social issues.

1) AHP analysis

First, we defined the goal: the assessment, according to the principles of sustainability, of the best area within Tuscany to install a fluid bed gasification biomass plant. Then, we set out the alternatives to choose from: the northern zone, the eastern zone, the South area and the West area.

The criteria on which the analysis is based, are the three constituent parts of sustainable development. They are shown, as well as the sub-criteria, in Table III.

TABLE III
Criteria and sub criteria of the sustainable AHP approach.

Criterion	Description	Sub criterion	Description
C1	Economic sustainability	SC1.1	NPV. This index represents the goodness of the investment, therefore the greater is its value and the most positive will be the impact on the economics of a sustainable development.
C2	Sociopolitical sustainability	SC2.1	Possibility of creating dedicated crops. As already stated, the creation of crops dedicated to energy production is considered a positive index on a social level, as it produces jobs and therefore welfare..
		SC2.2	Pollution. This has a negative impact on the welfare of future generations and that is why closely related to social sustainability
C3	Environmental sustainability	SC3.1	Amount of ashes. The ash produced by the combustion of wood chips release harmful substances into the environment: they are therefore a factor which adversely affects the environment.
		SC3.2	Ease of obtaining raw materials. This parameter is closely related to the environmental wellbeing as the availability of raw material is connected to its transport and, consequently, to the emissions arising from this [47]. The easier is the retrieval of biomass, the greater will be the positive impact on sustainability from an environmental point of view.

Figure 2 shows a schematic representation of the AHP architecture applied to our case study.

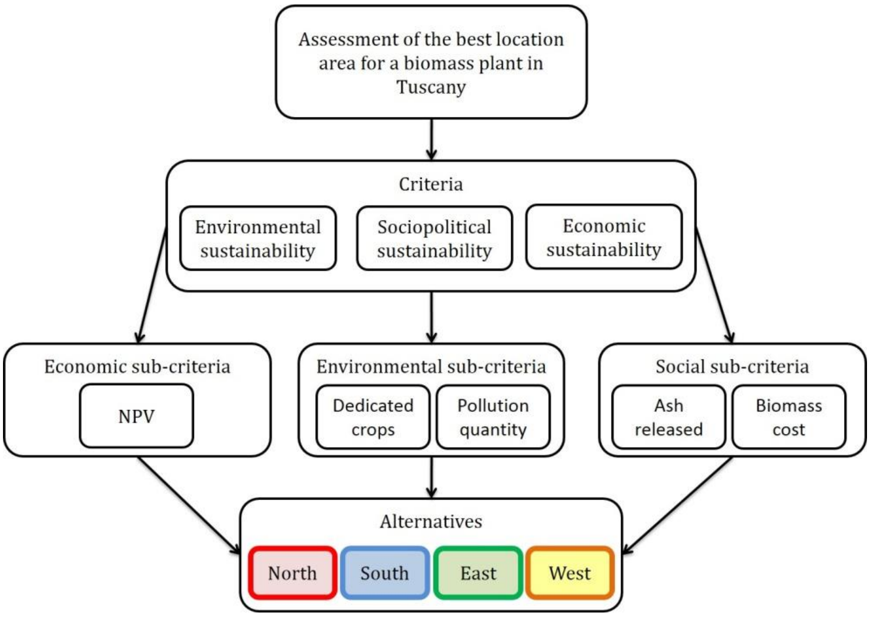

Fig. 2. Hierarchical representation according to the AHP model of the case study. The hierarchy starts from the top to descend down to the alternatives. is characterized by the goal, the criteria and sub-criteria, not interconnected, and the alternatives

The AHP analysis was not completed, since, in our case, the model is too restrictive. In fact, the process cannot be considered in a unidirectional way (a typical feature of the hierarchical structure of the AHP) since it is necessary to compare both alternative with respect to criteria and criteria with respect to alternatives. Actually, although each sub-criterion and then each criterion depends on the alternatives, the alternatives themselves depend on the criteria. Furthermore, you cannot affirm the independence between the elements of the same level, as the amount of ash and the ease of obtaining raw materials (environmental sub-criteria) strongly influence the pollution produced (social sub-criterion).

2) *ANP Analysis*:

The objective of the analysis remains the same highlighted within the AHP analysis, as well as the four alternatives, which remain the same. We defined the clusters, represented by the elements that in the AHP analysis were the criteria. Once defined the relationships and connections between all the characteristic elements of the network, the case study was represented as in Figure 3:

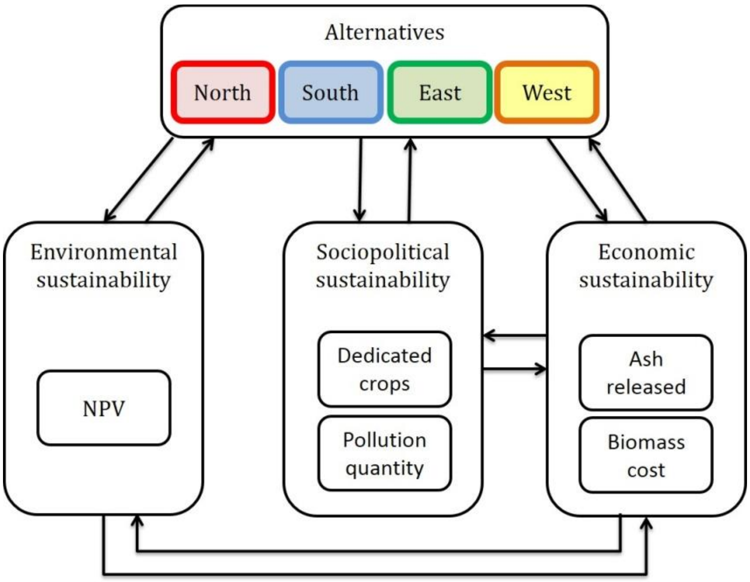

Fig. 3. ANP representation of the case study in a nonlinear network model. There are four clusters: one for the alternatives and the others for each one of the three aspects of sustainability. Within each cluster there are the elements that typify it.

Looking at the arrows of Figure 3, we see that each of the environmental clusters is affected by the alternatives and impacts in turn on the latter. In addition there are elements of the different aspects that influence each other. With the help of the software Super Decisions®, it was possible to make comparisons between the different clusters and between the nodes, allowing to analyse, with extreme ease and speed, the manner in which they influence each other and to get the priorities among the alternatives. In the second phase, a series of comparative pairwise evaluations were carried out, with the aim of determining the relative importance of the different elements with respect to a particular component of the network. From the judgments, the matrices of pairwise comparisons were defined and, in each case, we got the priorities of the respective components.

In addition to the comparisons between nodes, we have also performed comparisons between the clusters: This step was particularly important, as the importance given to the three aspects of sustainability, with respect to the alternatives cluster, depends very much on the decision maker and the interests it represents. Upon variation of the latter, one can obtain different preferences. Interpreting four different figures of decision-makers, four different scenarios have been identified.

1) Sustainable case: we consider a very general condition in which you decide to attribute the same importance to each aspect of sustainability.
2) Economic case: if the decision maker is the investor, he gives a greater importance to the economic aspect.
3) Social case: This occurs when the decision must be made by the administration, which focuses on the social aspects.
4) Environmental case: when the decision maker takes particularly care of the environment [56].

In Figure 3, we summarize the weights assigned to each of the aspects of sustainability in the four cases outlined above.

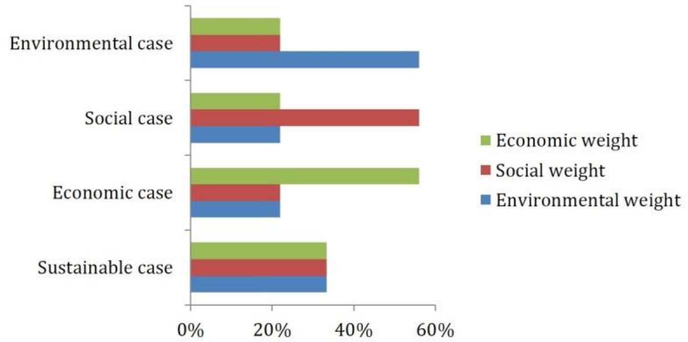

Fig. 4. Relevance of sustainability issues in the four case studied. In the diagram you can see the preferences of the decision makers of each individual scenario presented.

In the next step, we built the three supermatrixes. The initial supermatrix results to be the same for all four scenarios proposed, being composed of the priority vectors obtained from the pairwise comparisons, that do not change from one scenario to another. The weighted supermatrix, however, is different for each scenario, as it takes into account the different weights assigned to the clusters: it is obtained by multiplying the values of the initial matrix for the matrix obtained at the level of the comparison between the clusters. Even the limit supermatrix resulted different for each one of the scenarios considered. Analysing the values of each alternative within the supermatrixes, you could easily deduce what the analysis would identify as the most suitable. In this way we fulfilled the analysis, obtaining the for each one of the four scenarios considered.

Here are the results of the economic analysis and of the multi-criteria method performed by the ANP approach.

A. Economic analysis results

The parameter chosen to represent the goodness of the investment is the Net Present Value. Although this is not exhaustive and even if others could have been adopted, however, it may be considered sufficient for the purposes of this study. Results vary from one area to another, mainly due to the variation of the type of chips used. The graph in Figure 5 shows a better performance of the NPV in the South, followed by the West and from the East, to finish with the North.

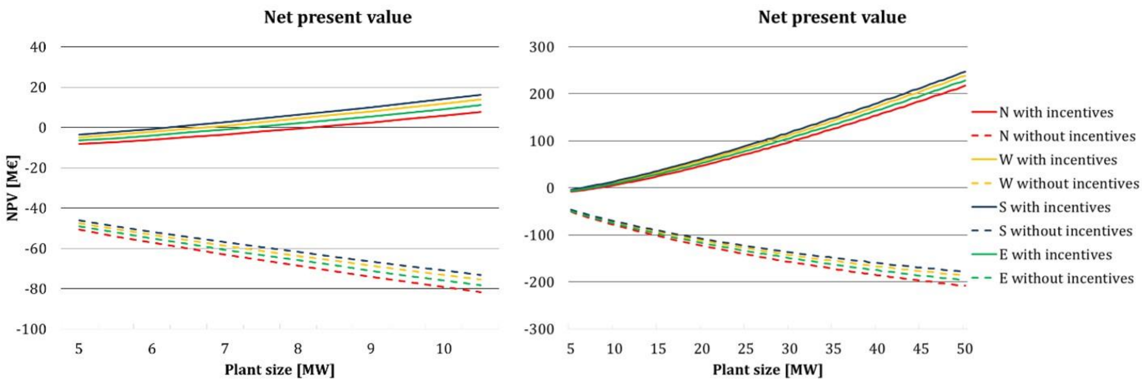

Fig. 5. NPV for the four areas of Tuscany. In the two above diagrams the NPV performance is shown, according to the plant size. The left part of the diagram shows the results for small size installations, while in the right part are represented all the possible potentialities evaluated.

The two different patterns are related to two different scenarios: with or without public incentives.

B. ANP analysis results:

Through the software Super Decision®, we have obtained the final preferences, summarized in Figure 6.

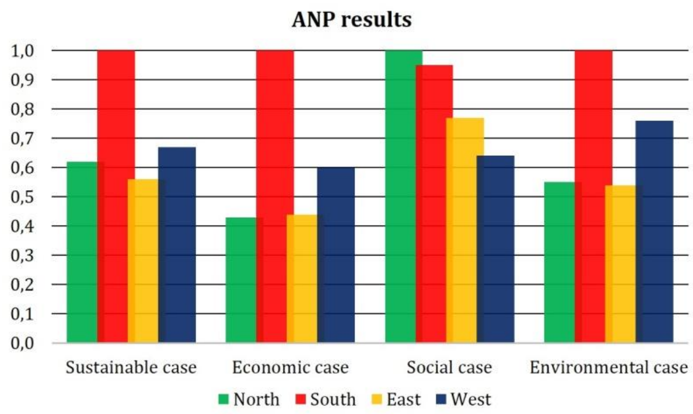

Fig. 6. Results of the ANP method. In the above figure are summarized the alternative preferences obtained through the analysis. The South area is desirable in three scenarios: sustainable, economic and environmental. The northern area is better in the social case.

From the diagram, we can appreciate a dominance of the southernmost alternative in three scenarios. However, as regards the social case, the North area appears to be the best alternative.

IV. Discussion

The goal to which this study aimed was to determine which was the best alternative among those identified within Tuscany for the installation of a biomass plant that uses wood chips as raw material. We wanted to highlight what was the importance of taking a sustainable decision and not strictly economic. The latter option, in fact, is too restrictive and tied back to an old concept of development, interpreted solely as profit. This explains why, after a first economic analysis, we performed a multicriteria evaluation of the alternatives, applying the ANP method.

As can be seen from Figure 5, in the case of absence of incentives, the NPV is always negative in the whole power range, for any alternative. In addition, its absolute value increases with the size. It can be assumed that, under these conditions, the investment is absolutely not affordable.

If we consider the incentives via the feed-in tariff, the investment becomes advantageous above a certain size of the plant. In particular the NPV passes from a negative value to a positive one in the following sizes of system: between 8 and 8.5 MW for the North, between 7 and 7.5 for the East, between 6 and 6.5 for the South and between 6.5 and 7 for the West area. The southern area is therefore the best alternative among those considered: this is determined by the strong influence that the operating costs have on the determination of the NPV. They mainly depend on the collection, transport and storage of biomass and its ashes. These parameters depend in turn on the amount of biomass consumed, which is influenced essentially by the LHV. This depends on the Anhydrous Calorific Value (which does not vary significantly from one area to another of Tuscany) and, especially, by the amount of moisture percentage of the wood chips. In conclusion we can say that the NPV is strongly influenced by the moisture percentage of the biomass, which, therefore, becomes a very significant parameter.

This conclusion is confirmed by the trend of the results, in fact the economic analysis proclaimed the South as the best choice, followed by West, East and North areas: this is precisely the order of the areas with increasing percentage moisture content.

As regards the results of the ANP analysis, in Figure 6 it is possible to find a predominance of the South alternative for the sustainable, environmental and economic cases.

Considering the economic case, it is intuitive to understand the reason why the South is the best alternative. In fact, in this scenario, it was decided to give precedence to economic aspects, achieving a very similar result to that of economic analysis. The South area, warmer and less rainy, as a matter of fact, has average moisture percentage values lower than other areas.

The reasons for the predominance of the South, in the sustainable case is very similar to the preceding one. In fact, in this case, the same importance is given to all aspects of sustainability, getting back the NPV as the more incisive factor.

In the environmental case the South alternative is still dominant, as the most influential parameters (in addition to the NPV, which always remains critical) appear to be the ease of obtaining the raw materials and the amount of ash produced. The values of the retrieval easiness are better in the South. Regarding the ash, although the type of wood chips available in South zone is characterized by a percentage value of ash greater than those of the other zones, the southern area is not the worst. One must keep in mind, indeed, that the ash actually generated depends on the amount of biomass used that, in the South case, turns out to be lower than in all other cases.

The final result of the ANP only changes in the social case in which the focus is on this kind of aspect, generally overlooked. The possibility of using dedicated energy crops is the driver for the decision. This option is greater in the North, as this area is characterized by a reduced use of the territory. The North is a mountainous area hardly cultivable: the possibility of planting dedicated crops is a positive factor because it is related to the exploitation of otherwise unused land and the likelihood that new employment is created. Furthermore, this land in not suitable for food crops, so the dilemma food or fuel is fixed at the origin [57] [58].

Performing a sensitivity analysis of the ANP results, it was verified that the method gives preferentiality to the South, until the importance of the social factor reaches the value of 56%: from here onwards the preferable alternative is the North.

Finally, reconnecting to the purpose of this research, we can say that AHP was able to compare different alternatives of location of gasification plants, in a broad regional context. This was done opportunely interpreting the concept of sustainable development and considering the moisture percentage of the biomass. The variability of the result shows that ANP is an extremely flexible tool in the hands of decision makers. It allows them to make the best decision in relation to the type of interest that they shall represent. Simply by varying the importance of each aspect, you can interpret the needs of the various figures involved, be they investors, governments or entire communities. This method, nonetheless, allowed the decision maker to enter not only quantitative parameters in the analysis but also qualitative, being a multi-criteria tool. In addition, the ANP turned out to be an extremely effective method to better implement the instances of sustainable development. The best alternative was indeed identified with an overall vision and not only from an economic or environmental point of view, and this is essential in the sustainability paradigm. Of course, the ANP integrates beautifully with other quantitative techniques. Any specific analysis is, therefore, useful as it allows to obtain more precise results concerning each one of the three aspects of sustainability. In future works we are willing to carry out a Life Cycle Assessment of each possible scenario and incorporate the findings into the ANP in order to obtain more precise and meaningful conclusions.

References

[1] J. Samouilidis and C. S. Mitropoulos, “Energy-economy models: A survey,” *Eur. J. Oper. Res.*, vol. 11, no. 3, pp. 222–232, 1982.

[2] P. Meier and V. Mubayi, “Modelling energy-economic interactions in developing countries: A linear programming approach,” *Eur. J. Oper. Res.*, vol. 13, no. 1, pp. 41–59, 1983.

[3] B. F. Hobbs and P. Meier, *Energy decisions and the environment: a guide to the use of multicriteria methods*. Kluwer Academic Publishers Boston, 2000.

[4] B. Hopwood, M. Mellor, and G. O’Brien, “Sustainable development: mapping different approaches,” *Sustain. Dev.*, vol. 13, no. 1, pp. 38–52, 2005.

[5] R. Putrus, “Accounting for intangibles in integrated manufacturing,” *Inf. Strat.*, vol. 6, pp. 25–30, 1990.

[6] T. O. Boucher and E. L. MacStravic, “Multiattribute evaluation within a present value framework and its relation to the analytic hierarchy process,” *Eng. Econ.*, vol. 37, no. 1, pp. 1–32, 1991.

[7] E. C. Özelkan and L. Duckstein, “Analysing water resources alternatives and handling criteria by multi criterion decision techniques,” *J. Environ. Manage.*, vol. 48, no. 1, pp. 69–96, 1996.

[8] K. S. Raju and C. R. S. Pillai, “Multicriterion decision making in performance evaluation of an irrigation system,” *Eur. J. Oper. Res.*, vol. 112, no. 3, pp. 479–488, 1999.

[9] S. D. Pohekar and M. Ramachandran, “Application of multi-criteria decision making to sustainable energy planning—a review,” *Renew. Sustain. Energy Rev.*, vol. 8, no. 4, pp. 365–381, 2004.

[10] N. H. Afgan and M. da Gracca Carvalho, “Energy system assessment with sustainability indicators,” in *Sustainable Assessment Method for Energy Systems*, Springer, 2000, pp. 83–125.

[11] N. H. Afgan, M. G. Carvalho, and N. V. Hovanov, “Sustainability assessment of renewable energy systems,” in *New and Renewable Technologies for Sustainable Development*, Springer, 2003, pp. 11–33.

[12] P. Zhou, B. W. Ang, and K. L. Poh, “Decision analysis in energy and environmental modeling: an update,” *Energy*, vol. 31, no. 14, pp. 2604–2622, 2006.

[13] J. P. Huang, K. L. Poh, and B. W. Ang, “Decision analysis in energy and environmental modeling,” *Energy*, vol. 20, no. 9, pp. 843–855, 1995.

[14] G. H. Brundtland, “Our common future (Report for the World commission on Environment and Development, United Nations),” *Our Common Future Rep. World Comm. Environ. Dev. United Nations*, 1987.

[15] D. Krajnc and P. Glavi\vc, “How to compare companies on relevant dimensions of sustainability,” *Ecol. Econ.*, vol. 55, no. 4, pp. 551–563, 2005.

[16] “http://www.sogesid.it/sviluppo_sostenibile.html.” [Online]. Available: http://www.sogesid.it/sviluppo_sostenibile.html. [Accessed: 22-Jun-2013].

[17] J.-J. Wang, Y.-Y. Jing, C.-F. Zhang, and J.-H. Zhao, “Review on multi-criteria decision analysis aid in sustainable energy decision-making,” *Renew. Sustain. Energy Rev.*, vol. 13, no. 9, pp. 2263–2278, 2009.

[18] D. Krajnc and P. Glavič, “Indicators of sustainable production,” *Clean Technol. Environ. Policy*, vol. 5, no. 3–4, pp. 279–288, Oct. 2003.

[19] “Chapter 40 - Sustainable Development,” in *Lees’ Loss Prevention in the Process Industries (Fourth Edition)*, Oxford: Butterworth-Heinemann, 2012, pp. 2507–2521.

[20] M. Gavrilescu, “2.66 - Sustainability,” in *Comprehensive Biotechnology (Second Edition)*, Murray Moo-Young, Ed. Burlington: Academic Press, 2011, pp. 905–923.

[21] F. Abulfotuh, “Energy efficiency and renewable technologies: the way to sustainable energy future,” *Desalination*, vol. 209, no. 1–3, pp. 275–282, Apr. 2007.

[22] B. Giddings, B. Hopwood, and G. O’brien, “Environment, economy and society: fitting them together into sustainable development,” *Sustain. Dev.*, vol. 10, no. 4, pp. 187–196, 2002.

[23] A. Demirbaş, “Biomass resource facilities and biomass conversion processing for fuels and chemicals,” *Energy Convers. Manag.*, vol. 42, no. 11, pp. 1357–1378, 2001.

[24] P. McKendry, “Energy production from biomass (part 3): gasification technologies,” *Bioresour. Technol.*, vol. 83, no. 1, pp. 55–63, 2002.

[25] D. Mohan, C. U. Pittman, and P. H. Steele, “Pyrolysis of wood/biomass for bio-oil: a critical review,” *Energy Fuels*, vol. 20, no. 3, pp. 848–889, 2006.

[26] T. Malkow, “Novel and innovative pyrolysis and gasification technologies for energy efficient and environmentally sound MSW disposal,” *Waste Manag.*, vol. 24, no. 1, pp. 53–79, 2004.

[27] T. E. Reed, “Biomass gasification: principles and technology,” 1981.

[28] D. Sutton, B. Kelleher, and J. R. Ross, “Review of literature on catalysts for biomass gasification,” *Fuel Process. Technol.*, vol. 73, no. 3, pp. 155–173, 2001.

[29] A. Beenackers, “Biomass gasification in moving beds, a review of European technologies,” *Renew. Energy*, vol. 16, no. 1, pp. 1180–1186, 1999.

[30] L. Devi, K. J. Ptasinski, and F. J. Janssen, “A review of the primary measures for tar elimination in biomass gasification processes,” *Biomass Bioenergy*, vol. 24, no. 2, pp. 125–140, 2003.

[31] Z. Abu El-Rub, E. A. Bramer, and G. Brem, “Review of catalysts for tar elimination in biomass gasification processes,” *Ind. Eng. Chem. Res.*, vol. 43, no. 22, pp. 6911–6919, 2004.

[32] [J. Han and H. Kim, “The reduction and control technology of tar during biomass gasification/pyrolysis: an overview,” *Renew. Sustain. Energy Rev.*, vol. 12, no. 2, pp. 397–416, 2008.

[33] E. Løken, “Use of multicriteria decision analysis methods for energy planning problems,” *Renew. Sustain. Energy Rev.*, vol. 11, no. 7, pp. 1584–1595, 2007.

[34] T. Gwo-Hshiung, S. Tzay-an, and L. Chien-Yuan, “Application of multicriteria decision making to the evaluation of new energy system development in Taiwan,” *Energy*, vol. 17, no. 10, pp. 983–992, 1992.

[35] T. Kaya and C. Kahraman, “Multicriteria renewable energy planning using an integrated fuzzy VIKOR & AHP methodology: The case of Istanbul,” *Energy*, vol. 35, no. 6, pp. 2517–2527, 2010.

[36] S. K. Lee, Y. J. Yoon, and J. W. Kim, “A study on making a long-term improvement in the national energy efficiency and GHG control plans by the AHP approach,” *Energy Policy*, vol. 35, no. 5, pp. 2862–2868, 2007.

[37] A. C. Caputo, M. Palumbo, P. M. Pelagagge, and F. Scacchia, “Economics of biomass energy utilization in combustion and gasification plants: effects of logistic variables,” *Biomass Bioenergy*, vol. 28, no. 1, pp. 35–51, Jan. 2005.

[38] F. Frombo, R. Minciardi, M. Robba, F. Rosso, and R. Sacile, “Planning woody biomass logistics for energy production: A strategic decision model,” *Biomass Bioenergy*, vol. 33, no. 3, pp. 372–383, 2009.

[39] A. A. Rentizelas, A. J. Tolis, and I. P. Tatsiopoulos, “Logistics issues of biomass: the storage problem and the multi-biomass supply chain,” *Renew. Sustain. Energy Rev.*, vol. 13, no. 4, pp. 887–894, 2009.

[40] L. T. Tran, C. G. Knight, R. V. O’Neill, and E. R. Smith, “Integrated environmental assessment of the mid-Atlantic region with analytical network process,” *Environ. Monit. Assess.*, vol. 94, no. 1–3, pp. 263–277, 2004.

[41] A. \cCi\ugdem Köne and T. Büke, “An Analytical Network Process (ANP) evaluation of alternative fuels for electricity generation in Turkey,” *Energy Policy*, vol. 35, no. 10, pp. 5220–5228, 2007.

[42] T. L. Saaty, “How to make a decision: the analytic hierarchy process,” *Eur. J. Oper. Res.*, vol. 48, no. 1, pp. 9–26, 1990.

[43] T. L. Saaty and L. G. Vargas, *Decision making with the analytic network process: economic, political, social and technological applications with benefits, opportunities, costs and risks*, vol. 95. Springer Science+ Business Media, 2006.

[44] T. L. Saaty, “Fundamentals of the analytic network process—Dependence and feedback in decision-making with a single network,” *J. Syst. Sci. Syst. Eng.*, vol. 13, no. 2, pp. 129–157, 2004.

[45] T. L. Saaty and L. G. Vargas, *Models, Methods, Concepts & Applications of the Analytic Hierarchy Process*. Springer, 2012.

[46] F. De Carlo, *Impianti industriali: conoscere e progettare i sistemi produttivi*, Terza edizione. Lulu.com, 2013.

[47] J. D. Murphy, E. McKeogh, and G. Kiely, “Technical/economic/environmental analysis of biogas utilisation,” *Appl. Energy*, vol. 77, no. 4, pp. 407–427, 2004.

[48] M. Azzari, *Atlante geoambientale della Toscana*. Istituto geografico De Agostini, 2006.

[49] “Analisi delle Potenzialità di Sviluppo di una filiera biomassa-energia nel contesto Toscano - Capitolo 8.pdf.” [Online]. Available: http://www.deistaf.unifi.it/link/biosit/index_files/Capitolo%208.pdf. [Accessed: 22-Jun-2013].

[50] V. Francescato, E. Antonini, and L. Zuccoli Bergomi, “Legna e cippato–manuale pratico,” *Aiel–associazione Ital. Energ. Agroforestali*, 2009.

[51] A., Compagnia delle RAFT - Rapporto sullo Stato delle Foreste in Toscana 2009, *RAFT - Rapporto sullo Stato delle Foreste in Toscana 2009*. Compagnia delle Foreste Srl.

[52] “The Biomass TradeCentre II project | home.” [Online]. Available: http://www.biomasstradecentre2.eu/Biomass-Trade-CentreII/. [Accessed: 22-Jun-2013].

[53] S. Canevese, V. Casamassima, A. Cavaliere, A. Frigerio, and G. Bruno, “Simulatore dell’impianto di riferimento a ciclo combinato,” *Rapp. Ric. Sist.*, vol. 8000725, 2008.

[54] O. Perego and A. Rossetti, “Casi de studio tecnico-economici’impianti termoelettrici alimentati a biomasa,” *Stima Della Propensione Alla Cogenerazione Ital.*, p. 49, 2011.

[55] “NETL: 2010 Worldwide Gasification Database.” [Online]. Available: http://www.netl.doe.gov/technologies/coalpower/gasification/worlddatabase/summary.html. [Accessed: 22-Jun-2013].

[56] Pope Benedictus XVI, “General audience,” *Apostol. Palace Castel Gandolfo Wedsnday*, Aug. 2009.

[57] L. R. Brown, “Food or fuel: new competition for the world’s cropland.,” *Worldwatch Pap. Worldwatch Inst.*, no. 35, 1980.

[58] A. Lipietz, “Food or fuel,” *Res. Rev.*, 2008.