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Multiple Criteria Analysis of Bio-energy Projects: Evaluation of Bio-Electricity Production in Farsala Plain, Greece

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ABSTRACT The evaluation of bio-electricity projects requires the synergy of different elements as it concerns a vertically operating activity and various stakeholders. Models related to each stage of bio-electricity production are pulled together within an integrated model of evaluation of the activity in the context of the European research program ALTENER, grouping multidisciplinary teams from Spain, Greece and Austria.

A database containing spatial information and expert knowledge as well as environmental models interact with the economic model. Bio-energy production is modelled, in this case, through micro-economic programming assuming that farmers supply biomass to a competitive market. As bio-energy chains are currently not viable in economic terms, government acts as a leader by determining the amount of transfer payments to be allocated so that the activity breaks even. These subsidies are justified to the taxpayers as fossil fuel substitution results in positive externalities to the environment.

A multi-criteria module completes the SDSS, enabling the selection among alternative bio-energy configurations. A case study illustrates the above methodology regarding bio-electricity project decision-making in the plain of Thessally, Greece. Plant capacity, siting and technology selections are determined simultaneously by the model taking into account local conditions. Cynara and miscanthus cultivated in arid and irrigated land are examined. Land resource is a constraining factor to the system, its availability is subject to increasing opportunity costs. Compromise solutions based on economic, environmental and social criteria are provided by the SDSS with costs that vary between 0.06 and 0.13 €/kWh at biomass marginal costs from 30 to 65 €/t.

KEYWORDS: Energy crops, Bio-electricity, Multi-criteria analysis, GIS, SDSS, Greece –

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1. Introduction

Designers of transportation systems, municipal and county engineers, environmental engineers increasingly rely on Geographical Information Systems (GIS) to manage and manipulate the large quantities of geographically derived data. Up to this moment, GIS have been applied to map biomass potential in specific regions in studies of forestry, industrial, agricultural or livestock residues. Bio-electricity project evaluation requires site-specific studies as, unlike conventional systems, bio-electricity plants are supplied with the biomass resource produced by farms situated in their vicinity. For this reason, GIS have been used extensively in many bio-energy studies since the 80s, such as the spatial model assessing potential of short rotation woody biomass in Hawaii to supply fuel to conversion facilities (Liu *et al.*, 1992). In that case, a system model for estimating biomass production, harvesting and transport costs was developed and applied to a Hawaiian island, while a GIS was interfaced with the biomass system model to access a database and present results in a map form. More ambitious works have attempted to assist bio-energy policy at the national level by providing policy makers with quantitative information, not only of an economic but also of an environmental nature, on potential biomass supplies from energy crops in the UK (Cole *et al.*, 1996) and in the US (Graham *et al.*, 1997, 2000). While GIS models can capture geographic variation that affects biomass cost and supply, they are often limited to deterministic analyses in spatial search. In search of suitable sites for the establishment of the bio-electricity plant, numerical and qualitative criteria are applied to selected siting factors and the area of focus is screened through digital map overlay procedures. However, these procedures can do no more than identify areas that simultaneously satisfy all the specified criteria; in other words, provide a feasible set of alternatives. The development of bio-electricity systems to substitute for fossil fuel-driven electricity generators is related to the search for a reasonable balance among environmental and economic objectives in the energy system. Additional techniques are then required to inform the user which site(s) offers the most promising characteristics for development with respect to different criteria. For this reason, it has been proposed to integrate multi-criteria evaluation methods with GIS assisted models (Carver, 1991).

This paper presents an interactive multi-criteria analysis tool based on the *reference point* method exploiting a spatial decision support system especially developed for the evaluation of bio-electricity projects. This methodology is illustrated by the presentation of a case study, implemented by means of the above tool, in the Farsala plain, Greece. In the next section, the structure of the integrated model is analysed and individual models involved are briefly presented. Then, in section 2.2, the micro-economic nature of the model is justified with the multi-criteria analysis methodology adopted is presented in section 2.3. The case study is detailed in part 3, where the supply curve generating procedure and the interactive multi-criteria decision making process are analytically described, followed by some conclusions.

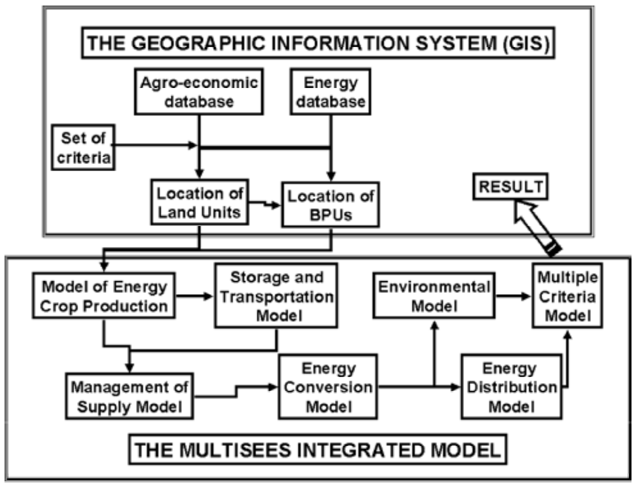


Figure 1 Schedule of data flow in the MULTISEES model. Source: Varela *et al.*, 2001.

2. Integrated BIo-Electricity Decision making (BI-EL.D.) Tool

2.1. Modelling structure

Several features of problems related to bio-electricity make difficult the development of decision-making tools. Modelling of such systems is usually related to a variety of scientific fields like biomass production, harvesting and transportation, conversion technologies and environmental impacts at all stages of this activity. Then integration of knowledge obtained in various fields is needed. For this purpose, several tasks have to be undertaken: a) development of a GIS platform and the computer-based information system to accommodate agro-economic and pedo-climatic data; and b) development of the models along the biomass energy chain (energy crop production, harvesting, storage and transportation, biomass supply, biomass energy conversion, environmental and multiple criteria models). Thus, decision-making on bio-energy requires analysis of a large amount of data and complex relations. The analysis has to be carried out by mathematical modelling coupling all sub-models in order to provide the decision-maker with an aggregate description of the problem and to support rational decision-making. Tools developed for such purposes can be identified as Decision Support Systems (DSS).

The final decision for the development of bio-energy is usually related to a balance of interests of various social groups. A DSS is a valuable tool for the evaluation of the consequences of given decisions and advises which decision would be the best for achieving a given set of goals. Thus, goals, such as the economic development of depressed areas, environmental objectives, technology integration and improvement, can be analysed through multiple-criteria model analysis. As Lotov (1998) suggests, the above features of issues related to environmental problems should be treated by the DSS on the basis of the following methodological principles:

- Aggregated economic and environmental performance indicators should be calculated by mathematical models to inform policy makers and all stakeholders of all feasible alternatives.
- The non-dominated set of alternatives has to be generated.
- Display all trade-offs among the indicators.

Based on the above principles and taking into account specific features related to bio-energy projects, a tool (software application built in VBA-Excel©) has been developed to assist decision-making for the establishment of bio-electricity systems in rural regions in Southern Europe (Varela *et al.*, 2001) based on project profitability, but also taking into account impact assessment of alternative bio-electricity schemes concerning the environment, local economy, agriculture, employment and public expenditure. Decision-makers can thus decide according to their preferences and viewpoints.

The integrated model consists of seven modules as shown in Figure 1. A brief description of each module is given below. A detailed account of linkages and information flows (input and output flows to and from the models) is presented in the MULTISEES final report to the European Commission (Varela *et al.*, 2001, Chapter 10):

Module I: Cost analysis of agricultural production (COSTOS, *ibid.*, ch.3)
This model is used to provide a detailed cost analysis of traditional and energy crops consistent with Net Present Value calculations. It can be used for the determination of the full cost of biomass production and financial comparisons between alternative uses of land.

Module II: Harvesting, storage and transportation model (*ibid.*, ch.4)
This model is capable of estimating harvesting, storage and transportation costs for biomass derived from energy crops. It has been structured to analyse biomass harvesting for both herbaceous and woody biomass.

Module III: Biomass supply model (BIELD-supply, *ibid.*, ch.5)
The supply module is used to estimate supply curves for energy crops. The model assumes that land use is decided primarily by individual farmers' responses to changing market and policy conditions.

Module IV: Energy conversion model (BIELD-conversion, *ibid.*,ch.6)
This model evaluates different technologies for biomass electricity generation. Four conversion technologies have been examined here (namely, fixed bed grate, fluidised bed steam turbine, fluidised bed gas turbine, co-generation heat and power steam turbine). All costs related to the power plant are taken into account and variables can be adjusted to local economic conditions.

Module V: Energy transport & distribution model (HEAD, *ibid.*, ch.7)
The energy distribution model calculates the costs of electricity and heat transport and distribution including all components between plant and consumers.

Module VI: Environmental model (approach based on GORCAM model, *ibid.*, ch.8)
Among all the different environmental impacts of energy systems the emissions of greenhouse gases (GHG) are identified as major pollutants. The environmental model analyses all possible GHG emissions. It is divided into two different parts assessing the GHG balances of: (i) land use changes (LUC), and (ii) energy systems (ENVION).

The Land Use Change model focuses on the carbon stock change; e.g., from agricultural cultivation to short rotation forestry. The greenhouse gas model is used for the GHG analysis of bio-energy and fossil energy systems based on the total life cycle. All GHG emissions - CO_2, CH_4 and N_2O - of construction, operation and dismantling of the facilities are included. The fuel chain includes all parts in electricity and/or heat supply, starting with the extraction of raw materials from nature and ending with the disposal of wastes from energy and material to the environment.

Module VII: Multiple criteria model (BIELD-criteria, *ibid.*, ch.9)
Multiple criteria analysis is used to explore biomass-to-energy project choices. Firstly, decision criteria and objectives have to be determined at the regional level. Their consequences should be identified. For instance, objectives may be the minimisation of energy cost and subsidies, the increase of agricultural income, or environmental sustainability. The model assists in illustrating conflicts and eventual trade-offs between objectives and in finding the most promising and compromising alternatives.

2.2 Economic rationality at the apex of the system

The supply model of biomass feedstock to the energy conversion plant complemented by the model of production cost assessment constitutes a regional micro-economic model. According to Moxey and White (1994), the economic module has to be placed at the apex of such a system in order to estimate supply curves of agricultural biomass for energy purposes, assuming that land use change is driven primarily by individual farmers' responses to changing market and policy conditions.

The regional micro-economic model:

- is capable of considering a wide range of different production activities and constraints and links between activities (e.g., rotations) and contains an input and output data structure easily transferable (directly linked to detailed cost analysis models)
- is able to incorporate an appropriate level of spatial precision
- is sufficiently flexible to cope with a wide range of policy instruments
- allows for exploration beyond historically observed activity levels
- is replicable (using available standard statistical data and accepted theoretical principles with minimal recourse to local surveys and *ad hoc* modelling techniques)

In this way, costs are calculated by the COSTOS (module I) for an average farm (arable cropping type) based on the hypothesis that all farms use standard mechanical equipment. Furthermore, it is supposed that each farm uses pumped water where drill equipment costs are annualised on a per hectare basis and included in the irrigation costs. Cost of production is calculated on an annual basis; that is, all costs concerning annual and perennial crops are annualised. The hypothesis that crops are harvested by individual entrepreneurs further simplifies the model, and makes it possible to solve separately each elementary model at the farm level as there is no factor causing direct interdependence among elementary land units (or farms). Thus, production costs are calculated for conventional and energy crops, where energy crop harvesting costs are calculated assuming biomass harvesters are operated fully during the year reaching a maximum utilisation level.

The farm-gate price of biomass feedstock is defined as the price in €/t that would provide the farmer, over the lifetime of the energy crop, a return to land and management equivalent to the expected return from growing the most profitable among the currently cultivated crops in the land unit under examination.

The estimation of the opportunity cost for switching to energy crop cultivation is based on the expected return on land and management of the current mix of conventional crops cultivated in a land unit. Data available allow for distinguishing between two categories of crops (winter and summer crops). No further distinctions are possible within those categories. Thus, optimization is performed assuming that the farmer has already minimised the area cultivated with the less profitable crops as much as possible, taking into account existing agronomic and demand constraints.

In this case, the minimum price at the farm-gate that would give sufficient incentive to the farmer to cultivate the energy crop is:

$$P_f = (max\{R_{Lu,c}\} + C_e)/Y_e \quad (1)$$

P_f = the minimum price to incite the farmer to produce energy crop feedstock
R_{Luc} = annual equivalent of return to land and management expected from the most profitable conventional crop suitable for cultivation in LU (Land Units)
C_e = annual equivalent of energy crop production costs
Y_e = annual yield of energy crop.

Aggregate supply curves for selected energy dedicated crops can be generated at the regional level, exploiting the above methodology fed by sophisticated information provided by GIS databases. Information related to the agricultural production supply curves is then provided to conversion models. Potential size of the fuel supply in a region, the size of bio-energy plants for its exploitation, the location of the fuel supply and the cost of biomass delivered to bio-energy plants can then be simultaneously estimated at the "satisficing" optimum for different sets of preferences in the decision space.

This exercise requires linked models to run simultaneously, and modelling to go a step beyond the simple juxtaposition of diverse economic and environmental elementary models, by incorporating all relevant models in a functional way. Such an integrated tool is able to evaluate different alternatives for energy crops on the basis of a multiple criteria analysis. It assists decision makers to adopt policies encouraging the introduction of energy crops into the regional energy system under current conditions of the Common Agricultural Policy, National Energy Policies and regional institutional arrangements and to adopt appropriate measures to improve the biomass-to-energy projects' competitiveness.

2.3. Multiple criteria methodology

As it has been proven elsewhere and confirmed by the first results of the study, biomass for electricity projects are, in most cases, lacking, especially in the first stage of their deployment. However, many factors converge to support biomass implementation, such as environmental concerns, rural development objectives and energy independence policies. A number of agents are involved in this activity, namely:

- Farmers who may decide to replace currently cultivated crops with energy biomass
- Cooperatives and entrepreneurs who may invest on harvesting machinery and other specialised agricultural, transport and storage equipment
- Entrepreneurs who may invest to build conversion and distribution facilities
- Government and regional authorities who may support financially the activity on behalf of taxpayers
- Politicians and environmental groups who may be in favour or against this kind of project (in favour with regard to the greenhouse gases abatement effect and against for reasons of local pollution problems such as soil pollution, noise and air pollution in the vicinity of the plant, etc.).

Each one of these agents has a number of interests that may be conflicting. For instance, public decision-makers decide upon allocation of budget funds and may consider budgetary constraints, but they may also be concerned about public pressure in favour of greenhouse-gas-emissions-abatement technologies. Other agents involved may base their decision on purely economic grounds. For instance, farmers expect to sell at prices that result in income greater than that from current activities.

Usually there is no alternative, which optimises all criteria simultaneously, so that one should be looking for the best compromise solution according to the decision maker(s) preference structure. It is important, for problems similar to the one tackled in this exercise, that the operation of multi-criteria analysis (MCA) be assisted by an interactive tool capable of accommodating all points of views for all interested parties, that could operate fast enough to permit the exploration of all possible alternatives and to enhance dialogue between decision-makers. The interactive MCA is implemented by a DSS tool in two components.

A. The core model specified and generated containing logical and physical relations between variables (forming its hard constraint structure).

Logical and physical relations of the core model define feasible solutions. In other words, the core model contains a set of variables and constraints that define a set, $X_{o,}$ of feasible solutions. If defined properly, X_o is a non-empty set. In the model in question, based on micro-economic analysis of two-level agro-energy chains, logical relations imply rational reactions of agents involved at the agricultural production and the industry levels. Thus, farmers are perceived as price takers that opt to maximise their income whereas industry aims at least to break-even. The multi-criteria module uses results of all linked models of the production, transport, storage and the conversion phase. It is fed directly by the conversion model that is a simulation-based model that predicts and evaluates consequences of decisions at the previous levels. For each level of biomass quantity produced by farmers, the conversion model can calculate capacities required, fixed and variable costs as well as minimum subsidies needed by industry to break-even for any of the four technologies examined. Also, it gives the CO_2 equivalent emission level. This part manages all models that consist of GIS software providing spatial information, production cost analysis models, harvesting, storage and transport models, and conversion model and constitutes the core model, namely the Bio-Electricity Decision-making integrated model (BIELD).

B. During the interactive procedure, goals and preferences are specified by the decision- maker (DM) in the form of additional (soft) constraints and variables. Constraints that correspond to the preferential structure of the DM are not incorporated in the core model in a conventional form because many interesting solutions would be left out of the analysis as infeasible. Therefore, constraints implying value judgements are introduced during the stage of interactive MCA to narrow the feasible space to a set of acceptable solutions. These solutions may differ according to the DM preferences and additional requirements. These additional requirements are arbitrary in nature as they may depend on who the DM is and whether or not his/her subjective preferences can be attained by the model. A properly designed interactive procedure should permit revision of all these specifications, thus exploring the decision space in the desired direction. The desired direction is traced by preferences expressed by the decision-maker in the form of desirable levels applied to each one of the criteria included in the DM's preferential structure.

The model includes *decision variables* (such as alternative areas cultivated by energy crops, technology options regarding harvesting, transport and storage as well as conversion process) and *intermediate or parametric variables* (such as institutional arrangements, prices to the farmers and capacities of conversion plants). In addition, in order to facilitate the process, the core model generates *variables defining potential criteria*. These variables may include possible objectives and goals (revenues to maximise and CO_2 emissions to minimise), performance indices (cost per unit of electricity produced and cost per unit of CO_2 emissions avoided), and outcomes (employment generated, agricultural surplus, subsidies required for viability, number of farmers that participate to the project, etc.).

Once all potential criteria are defined as outcome or auxiliary variables in the model the DM can select, among these, the most adapted to his/her preferences and interests or in the case where more agents assist in the decision making process, all participants may find information that conforms to their set of criteria.

The following criteria have been retained for the selection of the bio-electricity plant technology, size and site:

1. cost per unit
2. total amount of subsidies required to make the project viable
3. employment created at the conversion level
4. aggregate agricultural surplus
5. carbon dioxide equivalent emissions saved from substitution for fossil fuels
6. carbon sequestration from substitution of energy for conventional crops.

Models simulating agricultural production and the LUC environmental model calculate values of criteria 4 and 6 respectively, whereas values of the rest of the criteria are derived by conversion (criteria 1, 2 and 3) and the ENVION environmental model (criterion 5).

A key concept that is going to be used extensively throughout the multi-criteria process is that of non-domination. A *non-dominated* point corresponds to a feasible alternative, expressed, in the decision space, as a vector with dimensions equal to the number of criteria. It represents a feasible alternative that improves the value of one criterion, and deteriorates the value of at least one other criterion. The solutions, corresponding to non-dominated points, are *called efficient* or *Pareto optimal* solutions. Any non-dominated point is a candidate for representing the best compromise solution.

In theory, the Pareto set of optimal solutions is a subset of feasible solutions. In practice though, this subset may include just one or a finite but very large (so for practical reasons infinite) number of solutions, especially when numerous criteria are considered or, in some cases, all the feasible solutions. In similar problem structures the number of efficient solutions increases up to several hundred (Rozakis *et al.*, 2001). A procedure that can first generate Pareto efficient solutions has to be implemented in order to examine those that match up to the DM's preferences.

Moreover, given the difficulty of arbitrarily allocating a relative importance (weight) to each criterion, a method allowing the exploration of the efficient solutions and of possible trade-offs among criteria would be more appropriate than any method aggregating the criteria *a priori*. For this purpose, an interactive multi-criteria method based on a reference point approach was implemented (Wierzbicki, 1982). Basically, this approach projects desirable or aspiration levels expressed on the criteria onto the efficient frontier resulting in a solution corresponding to a specific bio-electricity scheme. Exploration is supported through an interactive adjustment of the aspiration levels on the basis of solutions generated at previous iterations. This approach has been used in various contexts, in particular in those involving environmental aspects (Stam *et al.*, 1992; Perny and Vanderpooten, 1998).

Projection of aspiration levels expressed by the DM is performed by optimising a scalarising function (*s*) that aims at satisfying the following requirements:

- *s* must generate efficient solutions only
- all efficient solutions may be generated by *s*.

For this purpose, the scalarising function derived from the augmented weighted Tchebycheff norm is selected:

$$s(z,\bar{z}) = \max_{h=1..p}\{\lambda_h(\bar{z}_h - z_h)\} - \varepsilon\sum_{h=1}^{p}\lambda_h z_h \qquad (2)$$

$$\lambda_h = 1 \Big/ \left(z_h^* - n_h\right) \qquad (3)$$

$\bar{z}$	reference point representing aspiration levels,
p	number of criteria (objectives),
ε	small positive value,
z^*_h	maximum value on criterion h (ideal point),
n_h	minimum value on criterion h, over the efficient set of solutions (nadir point).

When the feasible set consists of discrete alternatives of a finite number, the task of selection of the efficient alternative subset is quite easy and consists of comparing each solution to all others. A tool that formalises the process, defined above by the mathematical formulation, is required though in case of a big number of discrete alternatives. It has to be noted that whenever all efficient solutions are known, the projection can be performed using the simple weighted Tchebycheff norm (ε equal to zero so that the second term of (2) is omitted).

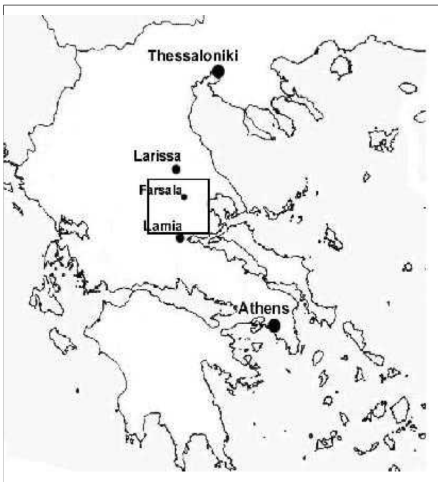


Figure 2 Study area

3. Case Study

3.1 Description of the region and spatial analysis

The region of study is a flat and hilly area, part of the Thessaly plain, located in central Greece with farm size larger than the average in the plain. The

Spot XS image used focuses on an area of about 55,000 ha large, around the Farsala municipality. Maps providing additional information (road infrastructure, electrical network, population concentration, district boundaries) have been geo-referenced and digitised based on the satellite image. The geographical layers along with the attribute tables were entered in a GIS, SPANS v.7.1, building a relational database. Land is divided into four types, as shown in the first column in Table 1, with corresponding surfaces appearing in the adjacent column.

Table 1 Options of substitution of energy crops (future) for current agricultural cultivation

Land type	Surface in ha	Energy crop potentially cultivated
Non-agricultural use	4340	-
Winter crops	12150	Cynara cardunculus
Summer crops (cotton, corn)	36200	Cynara cardunculus Miscanthus Sinensis
Pastures etc.	5160	-

Information concerning agricultural land is processed to distinguish land classes; land units with the same soil type, slope, and current land use belong to the same class. In this case study the number of classes sum up to 1090. Aggregate homogeneous land pieces (pixels) constitute elementary modelling units. Adjacent pixels that belong to the same class form a land unit (LU). In total there are 12395 LU. Land units may be larger or smaller than actual farms. Large land units are limited by the size of administrative districts (municipalities). In other words, a Land Unit can take at maximum the size of a municipality when all characteristics related to soil, slopes and current land use are homogeneous within it. Municipalities constitute the smallest administrative units for which agricultural statistics are available from the Greek National Statistics Service (ΕΣΥΕ).

3.2. Supply curves of energy crops and biomass feedstock

In order to estimate the cost of biomass raw material for energy conversion one has to estimate quantities potentially produced on each land unit in the area, as well as opportunity costs corresponding to energy crops for each individual land unit. Energy crop yields determine total quantity that a land unit may supply to the plant and consequently affect the particular shape of the supply curves. Information on yields of traditional crops is also very important as it determines the current activity benefits on which the opportunity cost of land depends.

As previously mentioned, two perennial herbaceous crops (cynara and elephant grass), which are of specific interest for Southern Europe, have been considered for energy purposes. Cynara cultivation has a lifetime of at least ten years with planting in the first year and the first harvest taking place in the second year and every year for the rest of its lifetime. Miscanthus is a cultivation that may live for 20 years with the same harvesting frequency as in cynara. Estimates of cynara and miscanthus yields under Greek conditions have been taken into account.

Expected yield of food and energy crops for each land class of the examined area is estimated by experts from the Agricultural University of Athens, by taking into consideration land suitability spatial information provided by the GIS. Fertility of land as presented in statistics as well as historical yields of food crops has been used to validate these estimates. Ideally, a growth model could provide these figures transforming yields to endogenous variables. Expected returns to land and management from conventional crops are calculated as presented in Table III in the Appendix.

Table 2 Surplus per hectare from energy crop cultivation

Land unit no: xx	Cynara	Miscanthus
Yield (t/ha)	25	50
Production cost (€/t)	49	48
Harvesting cost (€/t)	7	6
Transport and storage cost (€/t)	4	3
Total cost (€/t)	60	57
Market price (€/t)	65	60
Producer surplus € per ha	125	150

For an irrigated unit of land (for example land unit no. 51) substitution of cynara or miscanthus for conventional crops will take place if the condition in equation 1 is satisfied. As shown in Figure 1, data flow from the first element of the decision-making tool (that is, the database created by the GIS software) towards the integrated model. Information on LU characteristics and potential yields shows that cotton gives the highest return for land and management among conventional irrigated crops (cotton, corn). This value of 978 €/ha (last line in Appendix Table I) is used in place of "hired land rent" (in other words as an opportunity cost of land) in order to calculate the cost of production of energy plantations, candidates for cultivation on this land unit. In the same land unit, miscanthus costs 48 €/t and cynara costs 49 €/t before harvesting. Harvesting, transport and storage costs should be added to these figures to reach the unit cost at the plant gate.

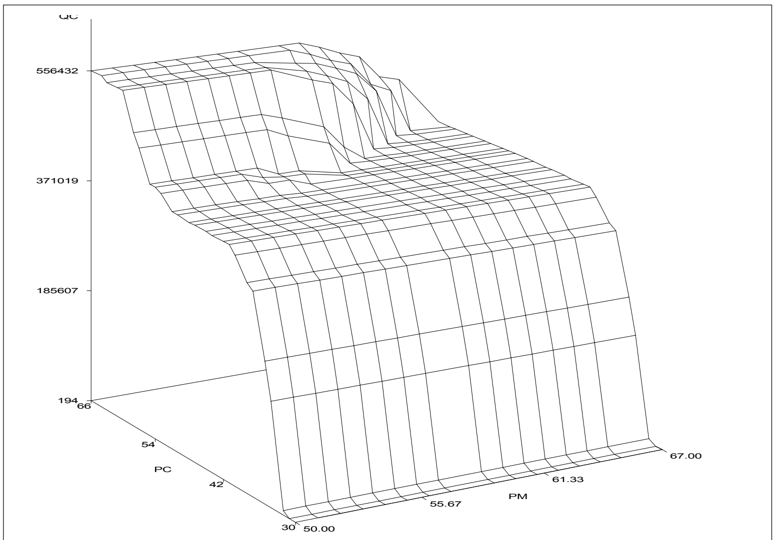


Figure 3a Supply of cynara (cultivated in irrigated and non-irrigated land units) competing with miscanthus for irrigated land

It can be observed that for prices of delivered biomass at the bio-electricity plant gate, 65 €/t for cynara and 60 €/t for miscanthus, the latter results in higher benefit per hectare (150 vs. 125 €/t) so that the farmers exploiting this particular land unit will supply only miscanthus. This selection depends on energy crop prices that the bio-electricity plant would pay to farmers. A grid of all possible prices at which energy crops can be sold at the plant gate is constructed. Prices that fall outside this grid are either too low, resulting in zero quantities being produced, or too high without any additional inciting effect. Successive conversion model iterations are then performed using all possible pairs of prices (p_{cynara} = {30, …, 65} and $p_{\text{miscanhus}}$ = {45, … , 60} in €/t) in order to obtain corresponding quantities produced. The relationship of prices to quantities is expressed by the supply curve concept. Note that these quantities are not determined independently; they take into account cross-price effects between energy crops, as shown in Figures 3a, 3b and 4.

In the horizontal axes we have prices (PC and PM stand for price of cynara and miscanthus, respectively) whereas quantities of cynara produced are shown in the vertical axis. One can observe that up to 45 €/t of cynara no interdependence appears regarding miscanthus price. This is explained by the fact that in this range only cynara in dry land units is profitable to produce. As miscanthus has to be irrigated there is no competition for this type of land. However, both energy crops can be substituted for conventional crops in irrigated land units, so competition between energy crops is observed. This is obvious when the price of cynara is set at higher than 65 €/t. In this case, aggregate production of cynara in the area of study reaches more than 500 thousand tons given a miscanthus price of less than 60 €/t. When this latter takes values higher than 65€/t, cynara production almost disappears from irrigated land units and it is limited only to the non-irrigated ones. Miscanthus production is shown in the graph in Figure 3b, for the miscanthus and cynara price ranges mentioned in the previous paragraph. The quantity of miscanthus produced is presented in the vertical axis.

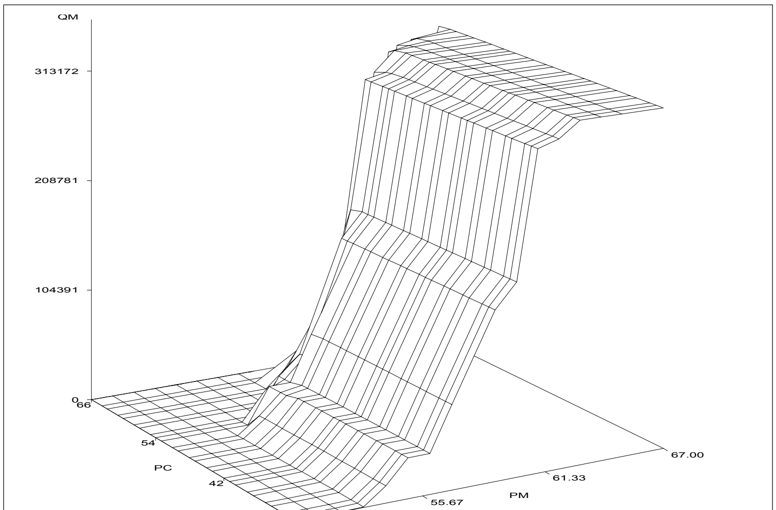


Figure 3b Supply of miscanthus competing with cynara for irrigated land.

Total biomass feed-stock supply to the plant depends on cynara (x-axis) and miscanthus (y-axis) prices. Given Low Heating Values (LHV) that determine energy produced (LHVdry of cynara is equal to 3767 kcal/kg; miscanthus LHVdry = 2696 kcal/kg), total biomass supply is expressed in Tcal. Biomass energy content thermal equivalent supplied at the plant gate at site A for different levels of cynara and miscanthus prices is shown in the graph in Figure 4.

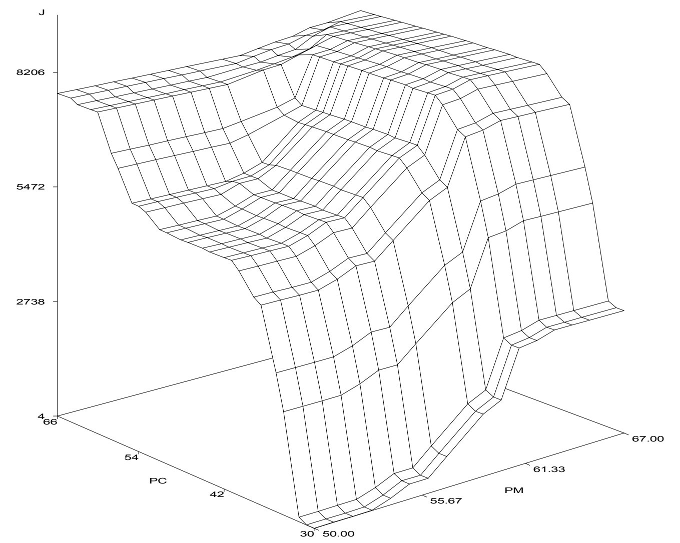


Figure 4 Total biomass feedstock supply (both cynara and miscanthus in Tcal)

Supply curves determine minimum prices equal to the marginal cost of biomass delivered at the plant gate required by farmers to supply the corresponding quantity. They can be used by conversion plants to estimate, in a realistic way, the cost of biomass feedstock and to locate production on the map. The supply curves generated during this exercise have been used by the conversion module of the integrated bio-electricity decision making model. Note that these curves are specific to a particular site as they include transport costs and consequently represent the cost at the conversion plant gate, as mentioned in the previous paragraphs. If the evaluation is performed for an area considering more than one candidate site, then the process of supply curve generation should be re-iterated as many times as the number of sites to be select.

3.3. Interactive multiple criteria decision making procedure

The study examines two candidate sites in the region of Farsala and four different technologies for bio-electricity generation of variable size (site pre-selection is done according to current transmission network capacity and demand for heat in the case of co-generation). In this case study, maximum capacities were constrained, basically due to heat demand limits, to less than 10 MW. Technologies examined are the fixed bed (grate) steam turbine, the fluidised bed steam turbine, the fluidised bed gas turbine, and combined heat and power steam turbine.

Alternatives, from which the decision will be taken, are generated by the BIELD model that links all particular modules of the system. The number of alternatives is defined by the number of discrete points constituting the supply curve multiplied by the number of technologies and the number of candidate sites (discarding alternatives that do not respect constraints such as those discussed above). Among all feasible alternatives there are twenty-four *non-dominated alternative solutions* (see the exhaustive list in Table II in the Appendix). In other words, there are twenty-four feasible solutions such that no other feasible solution can achieve equal or better performance for all criteria under consideration and strictly better for at least one criterion. The selection will be done among them on the basis of the DM's preference structure that is elicited from the DM interactively as explained below and then translated in *preference parameters*.

Once non-dominated solutions are known, the *payoff matrix* (Table 3) that informs the user of performance values for individual optimisation of each objective and conflicts between criteria can be created. The first line shows criteria values when the model minimises subsidies, corresponding to the annual amount required so that the plant breaks even for current electricity and heat tariffs (Table III in the Appendix).

The ideal alternative would be the vector in the diagonal (in bold) where all criteria attain their optimal value. It is obvious that this vector does not belong to the feasible domain so it is also called the utopian or ideal point. One can observe that, in this case, there are multiple optima for some criteria, namely cost per unit and labour. Cost minimisation is strongly conflicting with other objectives especially social (labour, and agricultural surplus) and environmental (CO_{2eq}

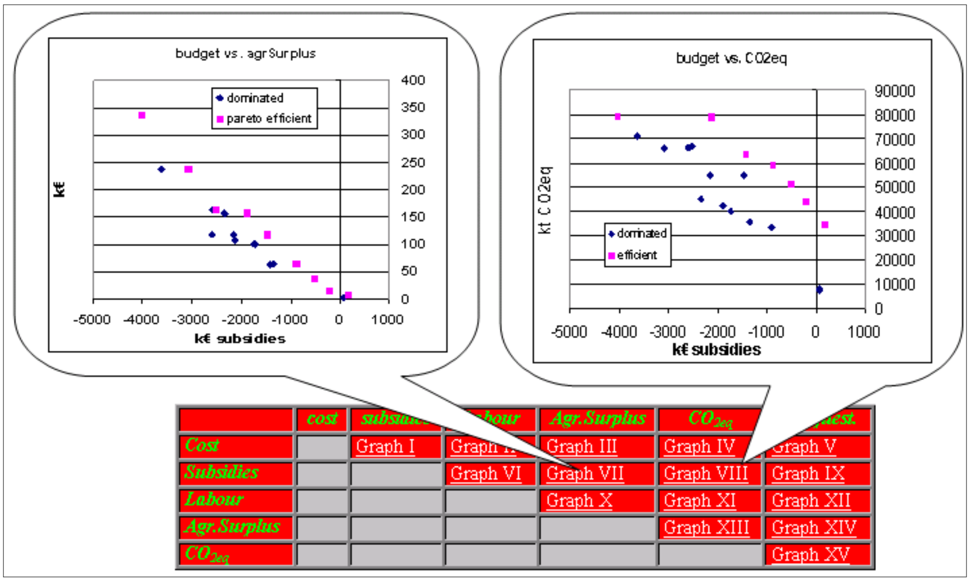
savings and C sequestration) ones. The four latter objectives improve more or less in the same direction. One would argue that we should discard some among these objectives. The reason for not doing so is that they concern different agents who may be present in the panel table. Furthermore, this reveals common, but not identical, interests of those agents as trade-off analysis will show.

Table 3 Farsala case study: Pay-off matrix with multiple optima

Criterion values after optimisation	Subsidies*	Cost* kWh $_e$	Labour	AgrSurplus	CO2eqSavs	CSeques
optimise for:	*k€*	*€/kWh$_e$*	*#*	*k€*	*ktCO$_{2eq}$*	*ktC*
Subsidies	**171**	-0.06	7	7	32886	1383
cost kWh e	75	**-0.050**	2	2	7182	303
cost kWh e	64	-0.050	2	3	7426	315
Labour	-4024.99	-0.130	**13**	339	73864	3370
Labour	-2133.91	-0.090	13	108	75834	3246
AgrSurplus	-4024.99	-0.130	13	**339**	73864	3370
CO2eqSavings	-2133.91	-0.090	13	108	**75834**	3246
CarbonSeques	-4024.99	-0.130	13	339	73864	**3370**

*Negative values of objectives to be minimised are given throughout the text. Negative subsidies mean outflows to the budget. Subsidies may be positive when an alternative results in benefits for a given tariff of electricity.

The above reasoning can be enriched by a thorough trade-off analysis based on the results of the case study. The decision making tool is able to display scatterplots for all pairs of objectives (a scatterplot/map matrix is used as decision aid in a location problem, see Malczewski, 1999). The concept of decision maps proposed by Lotov (1998) consists in graphically displaying trade-offs in cases of three or more objectives by exploiting altitudinal map techniques. It has not been used here because this case study is different from the Environmental Rehabilitation problem that Lotov tackles, as bio-electricity project alternatives are set as discrete choices that are not numerous, thus, resulting in discontinuous shapes. Moreover, it requires quite sophisticated software development effort. Nevertheless, one can observe that bi-dimensional scatterplots in the criteria space can give useful information as well as some insights that stakeholders can use during negotiation phase. Each graph treats a couple of objectives out of the six objectives of the study. This way fifteen couples are created to exhaust all combinations of objectives. Efficient frontiers are shaped in the criteria space.



	cost	subsid	bour	Agr.Surplus	CO$_{2eq}$	uest.
Cost		Graph I	Graph	Graph III	Graph IV	Graph V
Subsidies			Graph VI	Graph VII	Graph VIII	Graph IX
Labour				Graph X	Graph XI	Graph XII
Agr.Surplus					Graph XIII	Graph XIV
CO$_{2eq}$						Graph XV

Figure 5 Trade-offs* and efficient frontiers for all combinations of objectives

**trade-off: amount of achievement of one criterion that must be sacrificed to gain a unitary increase in the other one*

The user can select any bi-criterion couple from the table in Figure 5 to pop-up the corresponding scatterplot graph that distinguishes dominated from efficient points and shows the efficient frontier (linking square points in the graphs). After a glance at the graph, each party of the decision-making process can see against who he/she is in conflict and to what extent. The slope of the efficient frontier (trade-off curves) shows which interval in terms of criterion values is important or not. For instance, government can observe that the budgetary objective is in conflict with all but the objective of unitary cost minimisation. In graph VII (in Figure 5), one can observe as much as the budget minimisation objective is relaxed, the farmers' surplus objective value is increased. Regarding the greenhouse gas emissions this is not the case (graph VIII in Figure 5), as total budget can decrease by 2 million € (from 4 to 2 M€) with practically no effect on emissions. Consequently, there is no interest for environmentalists to insist on additional expenses to renewable energy in this interval. However, from the level of about 2 M€ and lower, any decrease in the budget affects emissions. This way all agents participating in the decision or the negotiation process defending their own interests or ideas can focus on the sensitive areas and build alliances.

Based on the pay-off matrix and trade-off bi-dimensional graphs between criteria the user can set the preference parameters. These consist of inter-criteria parameters (reflecting the relative importance of each criterion, e.g., weights), aspiration points (representing desirable levels on each criterion) and reservation levels (representing minimal requirements for each criterion). All preference parameters are presented in the table below.

Table 4 Preference parameters

to maximise	Subsidies	cost	Labour	agrSurplus	CO2eqSavings	CarbonSeques
	k€	€/kWh$_e$	#	k€	ktCO$_{2eq}$	ktC
Ideal[1]	171.0	-0.05	13	338.59	75834.0	3370.0
Anti-ideal[2]	-4025.0	-0.13	2	2.30	7182.0	303.0
Weight (λ_h) [3]	0.000238322	12.5	0.09	0.0029736	1.45662E-05	0.000326052
Aspiration level (target)	-1087.8	-0.074	9.7	271.332	64163.16	3370
Distance[4]	70	70	70	80	83	100
ex post distance[5]	51.04	25	54.5	46.01	47.81	54.77

[1] Ideal point: the solution where all objectives achieve their optimum value

[2] Nadir point: the vector containing the worst objective performances among efficient alternatives

[3] Weight equal to the normalising coefficient λ_h given by relationship 3.

[4] Distance is a percentage indicating the performance of the aspiration point with regard to individual objectives

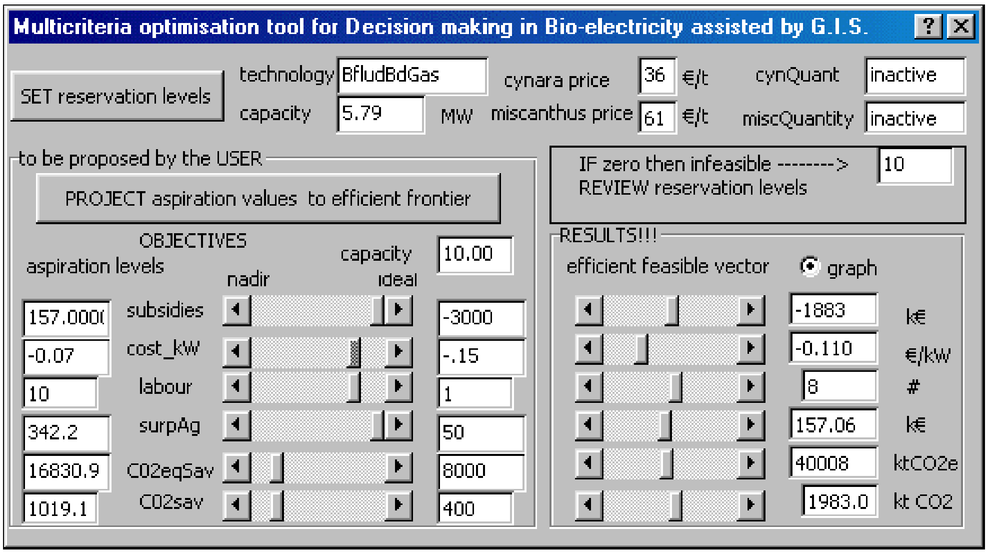
$$d_h = \left(\bar{z}_h - n_h\right) \Big/ \left(z_h^* - n_h\right)$$

[5] *Ex post* distance indicates the performance (%) of the proposed efficient alternative with regard to individual objectives

$$ex\_post\_d_h = \left(z_h - n_h\right) \Big/ \left(z_h^* - n_h\right)$$

A user-friendly dialog box containing all the above information is available in a visual form to enable the DM to perform all necessary operations related to the multi-criteria analysis, by means of which he/she can specify aspiration and reservation points, launch the MC module to find the compromise solution closest to his/her goal and finally visualise this proposed solution. A special macro procedure (VBA) maps the results illustrating the biomass supply associated with any proposed compromise alternative, so that the user gets a precise idea of the consequences of the selection in terms of biomass feedstock production spatial distribution.

The dialog box that is presented in Figure 6 contains preference parameters but also information required for the identification of the compromise alternative (capacity, prices of biomass feedstock) recommended by the MC module. Preference parameters are typed by the user in section "to be proposed by the USER" at the south-west side of the box. In this section scrolling bars assist the user to visualise aspiration levels in terms of relative distances from the ideal point (defined in relationship 4 above) for each objective as a percentage. For instance, when all scrolling bars are set to their extreme right end, it is the ideal point targeted. Respective values appear in the column at the left side in the section. Reservation levels can be set numerically in the right column of the section. The number of alternatives that belong to the feasible set is also shown in the box, recalculated every time the reservation levels are set. For highly demanding reservation levels there may be only a few or no feasible alternatives among which the selection can be made. This could be an indirect way of making decisions in the specific context. After all these parameters are set, the user presses the "PROJECT aspiration values to efficient frontier" button and the algorithm is solved resulting in the closest to the target efficient vector. This vector is shown in scrolling bars and values in the right side of the box (criteria values), while decision variable values corresponding to the proposed solution are shown in the upper part of the dialog box (technology, capacity, energy crop prices and quantities).



technology BFludBdGas
capacity 5.79 MW
cynara price 36 €/t
miscanthus price 61 €/t
cynQuant inactive
miscQuantity inactive

to be proposed by the USER

IF zero then infeasible --------> REVIEW reservation levels 10

capacity 10.00

aspiration levels	OBJECTIVES	ideal
157.000(	subsidies	-3000
-0.07	cost_kW	-.15
10	labour	1
342.2	surpAg	50
16830.9	C02eqSav	8000
1019.1	C02sav	400

RESULTS!!!

efficient feasible vector ● graph

-1883	k€
-0.110	€/kW
8	#
157.06	k€
40008	ktCO2e
1983.0	kt CO2

Figure 6 Dialog box of the interactive multi-criteria tool

When all objectives are sought to be optimised simultaneously, in other words, when the utopian point is the target, scrolling bars in the dialog box should be moved to their right end. In this case, the solution proposed in Bold Italics in Table II in the Appendix (values of criteria associated to it are shown in the same line), that corresponds to a plant located in site B near Kiparissos municipality with Fluidised Bed Gasifier technology using biomass bought at prices at the plant gate of 36 and 61 euro per ton of cynara and miscanthus, respectively (map in Figure 7).

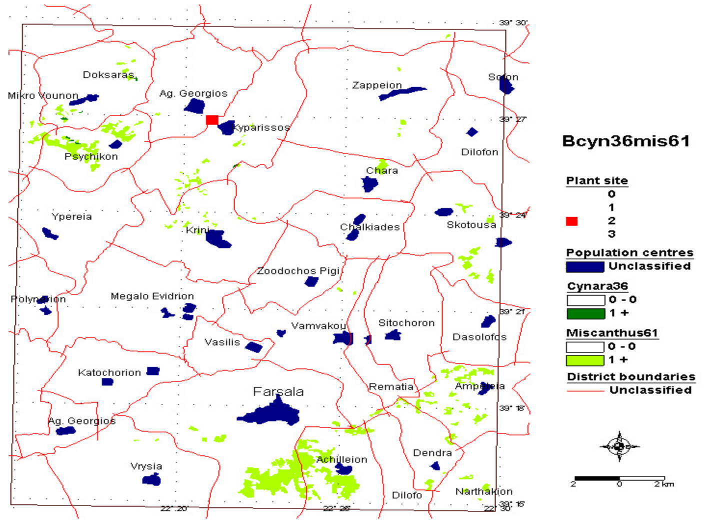


Figure 7 Efficient alternative corresponding to the target of the ideal point

This map distinguishes between energy crops and colours differently land units corresponding to different crops. As assumed and explained in the supply model section a LU cannot produce more than one energy crop. In the above map only miscanthus is cultivated.

If the user is not satisfied with this solution he can try to improve it with regard to a specific aspect. This can be done by selecting as aspiration level the solution proposed previously, when aiming at the ideal point, and try to improve it towards one or more directions. One can observe that site B is selected most of the time when subsidy minimisation is among the priorities of primary importance, and the technology of Fluidised Bed Gasifier performs better as a compromise solution as well.

However, when the subsidy target is more moderate, say set at about 1500 k€, then site A is selected along with the Fluidised Bed Gasifier technology of 7.5MW capacity. In both cases, irrigated land is used and miscanthus is cultivated with few quantities of cynara supplied.

4. Conclusions

The use of spatial DSS proves extremely useful to assist decision-making on bio-electricity project evaluation. An integrated model incorporating GIS and geo-referenced databases to economic and environmental models has generated a universe of alternatives regarding bio-electricity production in the plain of Farsala, Greece. Two energy crops compete for providing the bio-electricity plant with raw material, namely miscanthus and cynara, along with four different conversion technologies to electricity. Biomass cost is increasing with quantity penalising larger plants in terms of unitary kWh cost as supply curves show. Cost per kWh varies from 0.05 to 0.13 €/t, while subsidies required to ensure activity operation at break even may reach 4 M€ at maximum whereas in a few cases industry breaks even without any subsidisation. These cases concern Fluidised Bed Gasifiers of rather small size (from 1 to 5 MW electric capacity installed).

Supply curve estimation permits calculation of farmers' surplus, and calculation of economic welfare gains or losses. In order to consider socio-environmental objectives such as job creation and greenhouse gas emission abatement, decision making is performed on the basis of multi-criteria analysis. Because of the relatively large number of objectives (and interested agents), the resulting efficient alternatives, in this case, are numerous (twenty-four different bio-electricity configurations). An interactive tool developed to assist the DM process contains a multi-criteria algorithm based on the reference point method so that solutions proposed are the closest ones to the users' aspiration levels. This tool has proven handy and flexible as it permits search from any point in the decision space in whatever direction. Compromise solutions tend to confirm that Fluidised Bed Gasifiers are selected when all objectives are given equal importance but also when budget or environmental considerations prevail.

Perspectives to study broader areas with numerous possibilities of plant sites are given by applying the above methodology. However, local surveys and biological growth models should be used to improve input quality to the model regarding economic and agronomic information. The use of biological growth models will permit inclusion of site-specific environmental criteria such as nitrate pollution due to biomass production and to examine different cultivation techniques of energy crops. With regard to the multi-criteria module, improvements could bear on additional search modes especially in the decision variable space (enabling the user to modify the feasible space during the decision-making process).

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Appendix

Table I Current crop cost structure and rent to land and management (in €/ha). Energy crop cost structure and production costs per ton. Source: Model COSTOS.

Land unit no : 51	Cotton	Corn	Wheat	Miscanthus 40% moisture c.		Cynara 20% moisture c.	
Average annual dry yield (t/ha):	3.50	12.00	3.80	50	per ha	25	Per ha
Material inputs	235	319	189	491	9.8	89	3.6
Mech Equip Fuel (Own & Hired)	159	165	33	106	2	3	0.1
Own Mech Equip Maintenance							
Hired labour (mach. Operators & manual labour)	198	115	63	96	2	11	0.4
Hired Mech Equip, (Excluding Fuel and Labour)	872	856	170	548	11	20	0.8
Interest on ST Loans	78	73	23	62	1	6	0.2
TOTAL VARIABLE PAID EXPENSES	1,642	1,528	478	1,302	26	128	5
Hired Land Rent	0	0	0	978	20	978 (404)	39 (16)
General Overheads	100	100	100	100	2	100	4
Interest on LT Loans							
TOTAL FIXED PAID EXPENSES	100	100	100	1,078	22	1,078	43
Depreciation of own Mech Equip							
Cost of own (not paid) labour							
Cost of own Land							
Cost of own Capital	10	10					
TOTAL FIXED NOT PAID EXPENSES	10	10		10	0	10	0
TOTAL PRODUCTION COST	1,752	1,638	578	2,390	48	1,216 (642)	49 (26)
TOTAL SUBSIDIES	1,680	486	479				
SALES REVENUE	1,050	1,764	503				
RENT TO LAND AND MANAGEMENT	978	612	404				

Table II Population of non-dominated solutions (BCHP indicates CHP technology locate in site B)

technology	**prixCyn**	**prixMisc**	**capacity**	**subsidies**	**cost kWh e**	**Labour**	**agrSurplus**	**CO2eqSavings**	**CarbonSeques**
identification	**€/t**	**€/t**	**MW**	**k€**	**€/kWh$_e$**	**#**	**k€**	**k tCO2eq**	**k tCO2**
BfluidBdStm	34	61	5	-2339.84	-0.13	8	156.67	43038	1983.0
BfluidBdStm	36	61	5	-2340.84	-0.13	8	157.06	43038	1983.0
BfludBdGas	38	56	5.01	171	-0.06	7	7.42	32886	1383.0
BfludBdGas	34	60	5.47	-1728	-0.11	8	100.92	37846	1874.0
BfludBdGas	36	60	5.47	-1729	-0.11	8	101.3	37846	1874.0
BfludBdGas	34	61	5.79	-1882	-0.110	8	156.67	40008	1983.0
BfludBdGas	***36***	***61***	***5.79***	***-1883***	***-0.110***	***8***	***157.06***	***40008***	***1983.0***
BfludBdGas	38	57	6.37	-219	-0.070	9	16.01	42327	1855.0
BfxdBdGrtStm	38	61	7.09	-2569.27	-0.110	9	163.6	62929	3354.0
BfluidBdStm	38	59	7.29	-1416.25	-0.090	11	63.71	60978	2561.0
BfludBdGas	**38**	**58**	**7.32**	**-512**	**-0.070**	**10**	**38.58**	**48805**	**2184.0**
BfluidBdStm	36	62	7.88	-3626.69	-0.130	12	237.7	67776	3094.0
BCHP technology	38	61	8.04	-2521	-0.110	7	163.6	63615	3354.0
BfludBdGas	**38**	**59**	**8.44**	**-882**	**-0.080**	**11**	**63.71**	**56559**	**2561.0**
BfluidBdStm	36	63	8.59	-4024.99	-0.130	13	338.59	73864	3370.0
BfluidBdStm	38	60	9.02	-2133.91	-0.090	13	107.85	75834	3246.0
BfludBdGas	36	62	9.13	-3071	-0.110	12	237.7	62999	3094.0
AfludBdGas	32	52	1.09	75	-0.050	2	2.3	7182	303.0
AfludBdGas	32	53	1.13	64	-0.050	2	2.61	7426	315.0
AfluidBdStm	32	56	4.01	-1340.17	-0.110	7	63.88	34165	1540.0
AfludBdGas	32	56	4.65	-907	-0.090	7	63.88	31734	1540.0
ACHP technology	32	57	6.4	-1462	-0.120	6	118.66	51666	2857.0
AfluidBdStm	32	57	7.4	-2605.22	-0.110	11	118.66	63290	2857.0
AfludBdGas	31	57	7.52	-2147	-0.100	10	117.31	51990	2565.0

Table III Base case study data input to the models

Model	Parameter		unit	value
Agricultural production	Crop yields	Cynara	t/ha	10-30
		Miscanthus	t/ha	35-50
		Wheat	t/ha	2.1-5
		Cotton	t/ha	2.2-3.9
Conversion	Tariffs of electricity		€/kWh$_e$	0.057
	Price of thermal energy		€/kWh$_{th}$	0.030
	Tariffs of electricity when heat used		€/kWh$_e$	0.044
Energy distribution	Unitary cost		€/kWh$_e$	0.005