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EVALUATION OF RENEWABLE ENERGY POTENTIAL USING A GIS DECISION SUPPORT SYSTEM

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Abstract—A GIS Decision Support System has been developed for the evaluation of Renewable Energy Sources potential and the financial analysis of RE investments. A GIS database with data on wind, topography, urban areas, and special activities has been developed and used for the evaluation of theoretical potential through the spatially continuous mapping of Renewable Energy Resources. The available and technological potential are evaluated by the application of availability and technological restrictions. The evaluation of economical potential is performed by a precise estimation of the expected energy output and installation cost. The financial analysis based on the Internal Rate of Return, identifies the financial viability of alternative investments. The evaluation of wind energy potential for the island of Crete, Greece and the financial analysis of a wind park installation are presented as a case study. © 1998 Elsevier Science Ltd. All rights reserved.

INTRODUCTION

The exploitation of the substantial and inexhaustible Renewable Energy Sources (RES) potential is becoming economically feasible due to the rapid development of the relevant technologies. RES integration may be the key element of a new energy policy as it generally reduces energy losses, improves the stability and reliability of the energy system, minimises environmental impacts and results in significant fuel saving. The strong geographic and time discrepancies of RES in conjunction with their low energy flux indicates that energy

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consumption should take place within limited distance from the production site. Identification and estimation of RES supply, evaluation of energy demand profile, and development of the appropriate plans for RES integration constitute the basis on which a realistic regional energy policy should be formed.

Financial or legal incentives for RES development, that exist in many European countries, have motivated new types of interests. Governments, utilities, private investors and local authorities become active actors in the energy planning process [1]. Governments, as the major energy policy makers, are concerned with the sustainable development through a large scale integration of RES into the energy system. Utilities, as the traditional energy administrators, pay more interest in the reliability of the energy system and production costs. Investors, are mainly interested in the profits that can be obtained by RES investments and local authorities are concerned with the harmonisation of the local needs to the proposed actions. Governments can provide the legal framework and financial incentives whereas local authorities can protect investments on specific sites providing the funds for the infrastructure interventions.

Energy actors, need the means to determine the existing opportunities and plan their actions in a general framework of principles and procedures for the development and evaluation of RES integration scenarios. Previous research in RES has focused on the identification of a realistic potential based on the static mapping of RES [2], available measurements [3, 4], and modelling [5]. The analysis of alternative RES exploitation scenarios has emphasized on the use of economic indices in order to propose the most appropriate solution, [6, 7]. The full introduction of the specific local characteristics, the technological and technical aspects and economic factors into the evaluation of the RES potential had not been the focal point until recently, mainly due to the lack of tools able to correlate the different types of information, [7].

In the present work the problem of identification and estimation of RES supply is tackled. The developed methodology introduces a set of sequential steps for the evaluation of wind potential as *theoretical*, *available*, *technological* and *economically exploitable* based on the normalisation of each type of potential and the determination of the restrictions applicable. The following actions are implemented in each level of analysis:

- Estimation of the existing RES potential.
- Assessment of the influence of local characteristics.
- Evaluation of the restrictions imposed by the available technology.
- Assessment of the expected economic profits.

The method aims at the evaluation of the spatial distribution of energy supply in a region and combined with the energy demand profile can point out actions and interventions needed to improve an existing energy system.

The spatial distribution of RES potential, the inherent RES dependence on site specific characteristics and the overall cost dependence on spatial attributes make Geographic Information Systems (GIS) an indispensable tool for energy management. The developed methodology introduces the GIS as the framework for incorporating all the regional social and geographical characteristics. The main advantages of using GIS technology is its flexibility in handling data available on different levels of spatial analysis and its ability to highlight the spatial interrelations between data sets.

A Decision Support System (RES-DSS) has been developed, which incorporates the advantages offered by the rapidly developing GIS technology in order to fully exploit RES databases and handle efficiently the geographic characteristics that affect RES potential and energy cost.

METHODOLOGY

The methodology which is presented applies to different types of RES since theoretical, available, technological and economical potential have the same defining attributes and behaviour regardless of which type of energy source is considered. The algorithm and the implementation into the GIS environment will be presented for the wind energy potential.

Method

The evaluation of wind potential is conducted by a sequence of steps which represent sets of restrictions on the exploitation of the potential. In the first step, the theoretical potential is estimated, and then the available and technological potential are assessed. Finally the economical potential is estimated on the basis of appropriate financial indices and the analysis of alternative investment scenarios.

The *theoretical potential* is defined by the maximum wind energy output in a region. It is determined by all the available sites in that region with adequate wind speed. No availability or technological restrictions are considered, [7]. The *available potential* is defined as the part of the theoretical potential that can be harvested easily and without any environmental impacts [8]. The restrictions defining the available potential act as exclusion criteria which eliminate areas with characteristics prohibiting the exploitation of wind energy. Such areas are:

- High altitude areas, due to access difficulties.
- High slope areas, due to access difficulties.
- Areas near towns, for safety reasons and to minimise visual impact.
- Areas near airports, for safety reasons.
- Areas near archaeological sites, to minimise visual impact.
- Protected areas (forests and National Parks), due to legal constraints.

The *technological potential* is defined by the energy that can be harvested using existing technology and is bounded by the characteristics of the commercially available wind turbines. The *economical potential* is defined as the energy that can be harvested using economically feasible installations. Infrastructure or technical constraints (road and grid network) and economic aspects (energy production cost, expected profits) fix the limits of the economical potential.

The methodology developed is applicable to different types of energy actors such as energy policy makers, utilities, private investors or local authorities. Each decision maker defines the economical potential according to his/her specific requirements. The developed Decision Support System can provide the different types of information needed by each energy actor and offers the common framework for comparing decisions and evaluating proposed actions. For the information required by energy policy makers, RES-DSS estimates the available and technological wind potential which represents the maximum energy supply that can be obtained. RES-DSS estimates the energy production cost for each of the areas with adequate available potential and the Internal Rate of Return (IRR) of specific investments which is the information required by utilities or private investors. RES-DSS, also, compares different scenarios based on the expected energy production, the energy cost and the needed interventions setting, thus, the framework for conversation among utilities, private investors and local authorities.

GIS implementation

RES-DSS has been developed in MAPINFO Professional, a GIS environment under WINDOWS 95. The decision procedure is based on the method described above and makes use of the extensive GIS database, that has been developed, on geographic data related to all essential factors that affect the RES potential. The dependence of RES potential on spatial attributes presumes that all available data should be transformed into geo-referenced objects sets sharing the same characteristics and interacting on the basis of their geographic relation. The tools which implement the spatial interactions between geographic objects are provided by the GIS platform, but the design of the objects sets and the definition of their behaviour is a subjective procedure. The objects that will be used, and of course, the accuracy and completeness of the available data have a decisive impact on the quality of results. Figure 1 presents the interrelation between the RES-DSS and the decision maker and provides an insight to the developed database and modules.

The theoretical potential is evaluated and presented as a digital map. Each region of a certain wind speed is represented by a polygon. In RES-DSS, wind speed data, necessary for the estimation of theoretical wind potential, are modelled as region objects characterised by the attribute "wind speed".

The available potential is presented in the same way after the application of the restrictions on the regions that constitute the theoretical potential. Altitude and slope data are modelled as region objects characterised by their "altitude" and "slope", respectively. Towns, airports and archaeological sites are modelled as points and their behaviour depends on their special attributes (i.e. the minimum allowable distance for installation of a wind park near an airport is different than that of a town). The areas of the theoretical potential which overlap the areas of altitudes or slope over threshold values, set by the user, as well as buffer areas around towns, airports and archaeological sites are excluded.

The technological potential is evaluated on the assumption that all the available sites are fully exploited by wind farms with the selected type of wind turbines. In order to introduce the technological restrictions for wind exploitation, a database of the characteristics of commercially available wind turbines (nominal power, hub height, rotor diameter, cost, power curve) has been developed [9]. After the selection of the wind turbines, an average produced energy density is presented as a thematic layer pointing out the sites where the highest energy production may be expected.

The economical potential is determined by the existing road and grid networks since their condition affects the viability of investments. The available data related to the grid network are modelled as lines characterised by the maximum power they can transmit and their expansion cost. These data are then used to assess the possibility to exploit all the available potential in a site because the power that will be installed is bounded by the capacity of the available power line. The available data on the road network are modelled as lines characterised by the road status and the construction cost for its expansion. The construction cost of the road up to the wind park generally increases the capital cost of an investment affecting its feasibility. The economical potential is determined either on the basis of energy production cost or the feasibility of a proposed investment.

The energy production cost is estimated in terms of levelled electricity cost (LEC), that is the electricity production cost of each area, if the proximity of the installation to the road

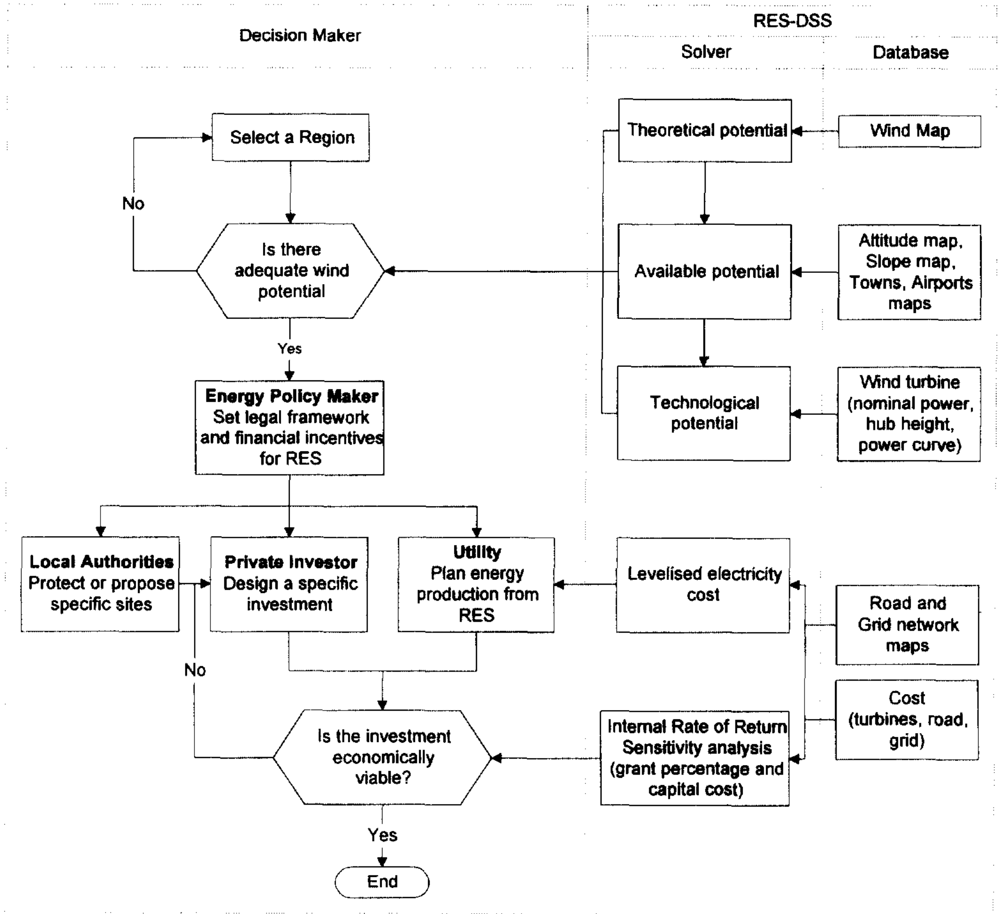

Fig. 1. RES-DSS algorithm.

and grid networks and the wind turbines that will be used are taken into account. The results are presented as a thematic map that points out regions with low energy production cost.

The feasibility of proposed investments is determined by the Internal Rate of Return (IRR) on equity which is estimated after the user designs a specific wind park and the necessary road and grid extensions and sets the financial scheme under which the wind park is developed. Additional information may be derived by a sensitivity analysis on the grant percentage and capital cost. When the IRR is not acceptable, alternative wind park designs or infrastructure interventions may be adopted and the comparison between different alternatives can point out an acceptable solution.

The available sets of data are modelled as distinct map tables. In each region, the necessary map layers are created and presented in a Map window. The same window is used for the presentation of the intermediate and final maps and thematic layers after the evaluation of the potential at each level of analysis. Graphs and tables are used to portray energy production and financial analysis results.

CASE STUDY: WIND POTENTIAL IN CRETE

The energy system of the Crete island is a typical case of a remote and autonomous system which relies heavily on energy supplies from the mainland. Crete presents high wind potential, as prior assessments have pointed out. The exploitation of this potential drew, recently, the interest of local authorities and private investors.

The data for Crete used in the present case study are:

- Digital map of wind speed regions (6, 7 and over 8 m s^{-1})
- Digital map of coastline
- Digital map of altitude lines with 200 m increment
- Digital map of slope curves for slopes 0–70% in 10% increments
- Digital map of town location and other demographic data
- Digital map of the location of airports and archaeological monuments
- Digital map of the grid network with information on the maximum power transmitted by each line
- Digital map of roads with information for the construction cost of a new road
- Characteristics of commercially available wind turbines [9].

Figure 2 presents the political map of Crete with airports, archaeological sites, towns and roads. Figure 3 presents the altitude lines and the grid network for Crete.

The available potential for the case study has been evaluated by the application of the following restrictions:

- Minimum allowable wind speed 6 m s^{-1}
- Maximum allowable altitude 1000 m
- Maximum allowable slope 60%
- Minimum distance from towns 1000 m
- Minimum distance from airports 2500 m
- Minium distance from archaeological sites 2000 m

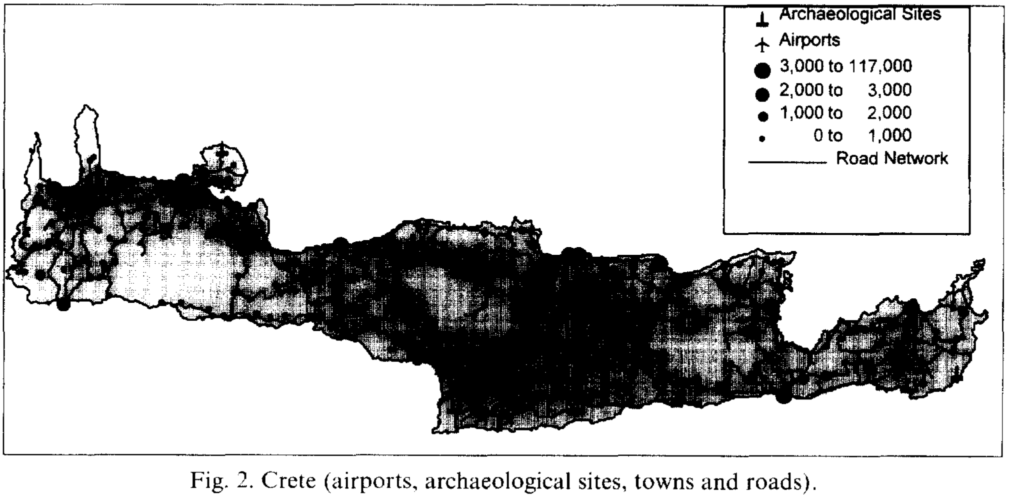

Fig. 2. Crete (airports, archaeological sites, towns and roads).

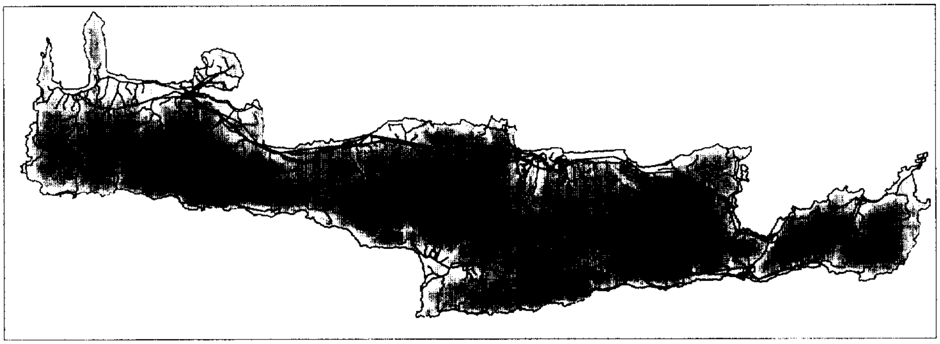

Fig. 3. Altitude lines and grid network for Crete.

Figure 4 presents the available wind potential in Crete and the sites for which detailed financial analysis has been conducted.

The technological wind potential for the case study has been estimated using a wind turbine of the following characteristics:

- Nominal Power: 250 kW
- Rotor diameter: 29.7 m
- Hub height: 31.5 m
- Cost: 733 ECU/kW

The economical wind potential for this case study has been evaluated on the basis of levelled electricity cost and an IRR on equity.

Levelled electricity cost has been evaluated on a 2 × 2 km grid. Available wind potential has been identified and the expected electricity production and energy cost have been estimated for each cell of the grid assuming that the entire area of each cell has been covered by wind turbines. Figure 5 presents the resulted levelled electricity costs for each cell and points out the areas of less costly energy production.

The most promising sites, for which financial analysis has been completed, have been selected on the basis of existing measurements indicating very high mean annual wind

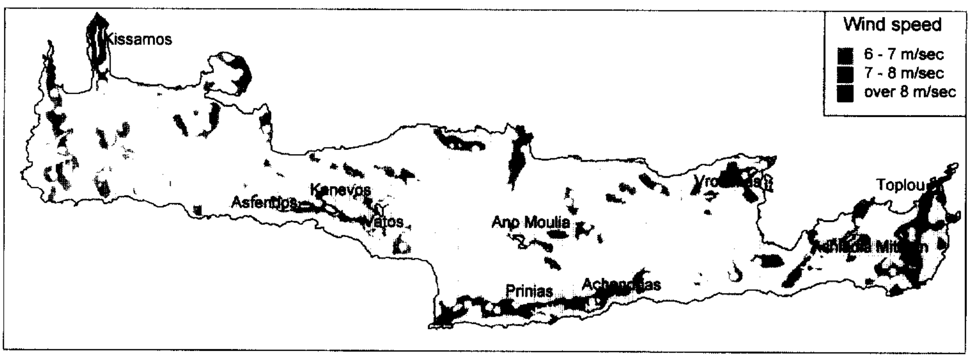

Fig. 4. Available wind potential and wind parks considered.

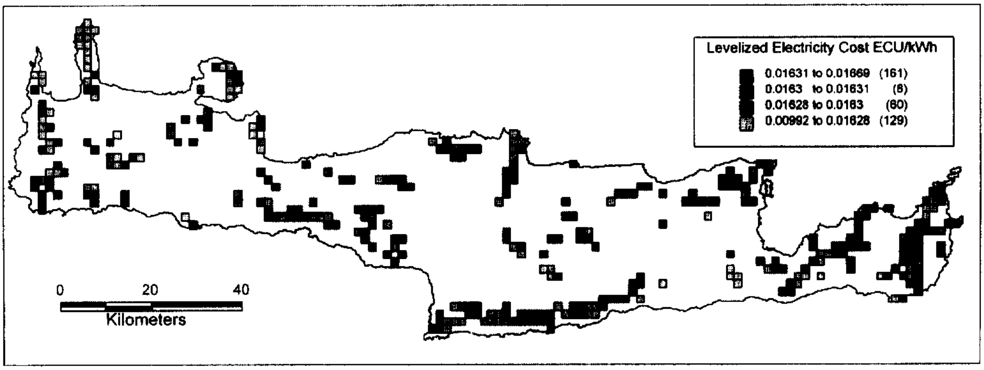

Fig. 5. Levelled electricity cost.

speeds. For each site a wind farm has been designed and necessary interventions to the grid and road networks have been taken into account. The closest power line and road have been extended up to the wind farm. The expected IRR on equity for each one of the proposed sites has been estimated taking into account the installation costs (turbines price, transportation and foundation costs, and infrastructure costs), the operational and maintenance costs, the electricity selling price, and the available grants. The basic investment scenario considered is the following:

- Electricity selling price: 0.064 ECU/kWh
- Operation and maintenance costs: 2.2% of the total capital cost
- Construction period: 2 years
- Inflation rate: 8%
- Life time of investment: 15 years
- Grant 20% of the total investment cost

Figure 6 presents the IRR for each site according to this financial scheme. The economic

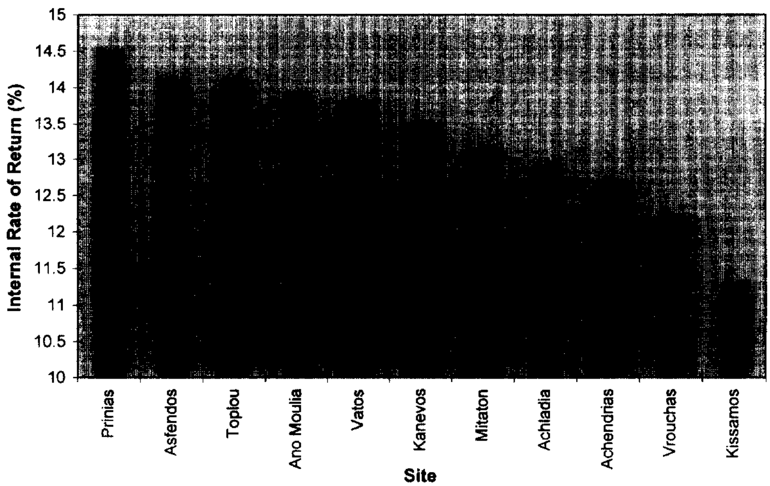

Fig. 6. Internal rate of return for the sites considered.

viability of the potential investments is indicated and investors may select the most attractive of them for further investigation.

For the site of Prinias, which has the higher IRR, an alternative installation has been considered and the wind park has been connected to the high voltage grid by a higher capacity line in order to increase the installed power. Figure 7 presents a detailed map of the area and the new line that has to be constructed in each case. For both cases the following uncertainties are considered:

- Available grants in the range of 0–40% of the total investment cost (dictated by the existing financial framework concerning RES in Greece)
- Capital cost increase by 30% or decrease by 10%

The sensitivity analysis for grants percentage in the case of the low capacity line is presented in Fig. 8 and shows that IRR is in the range of 10.5–21% as the grants range from 0–40% of the total investment cost.

Figure 9 presents the sensitivity analysis for the grants percentage for the case where the longer high capacity power line is used and shows that the IRR is in the range of 14–26% as the grants range from 0–40% of the total investment cost. The comparison between the short low capacity line and the high capacity line favours the second scenario. In addition, the sensitivity analysis for the grants percentage in both cases shows that the expected profits of the proposed investment will increase in the case where the local authorities could contribute additional grants (i.e. construction of the power line and road extensions).

Figure 10 presents the effect of the fluctuations of the capital cost that may emerge during the construction period and shows that the IRR is 10% in the case that the capital cost is increased by 30% and is increased at 16% if the capital cost is decreased by 10%.

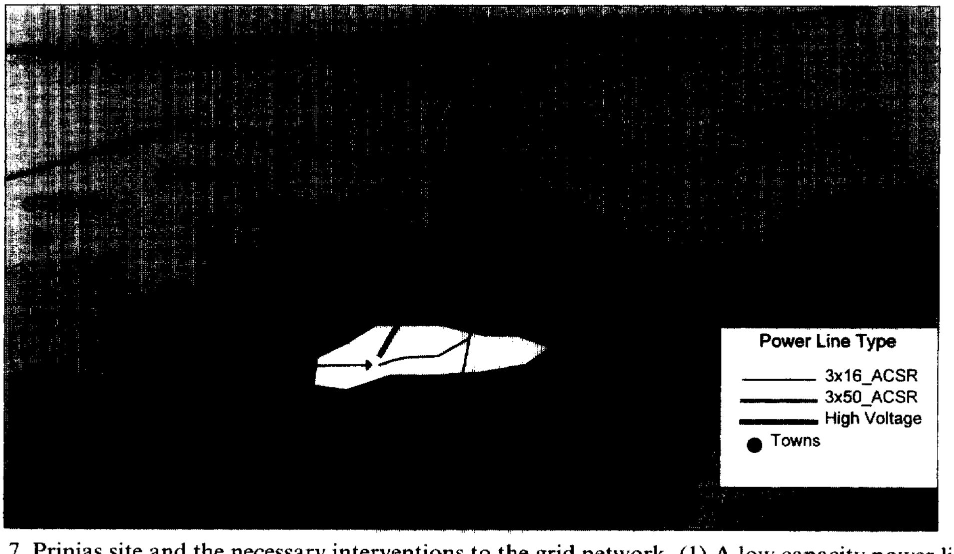

Fig. 7. Prinias site and the necessary interventions to the grid network. (1) A low capacity power line is connected to the nearest existing grid line. (2) A high capacity power line is connected to the high voltage grid line.

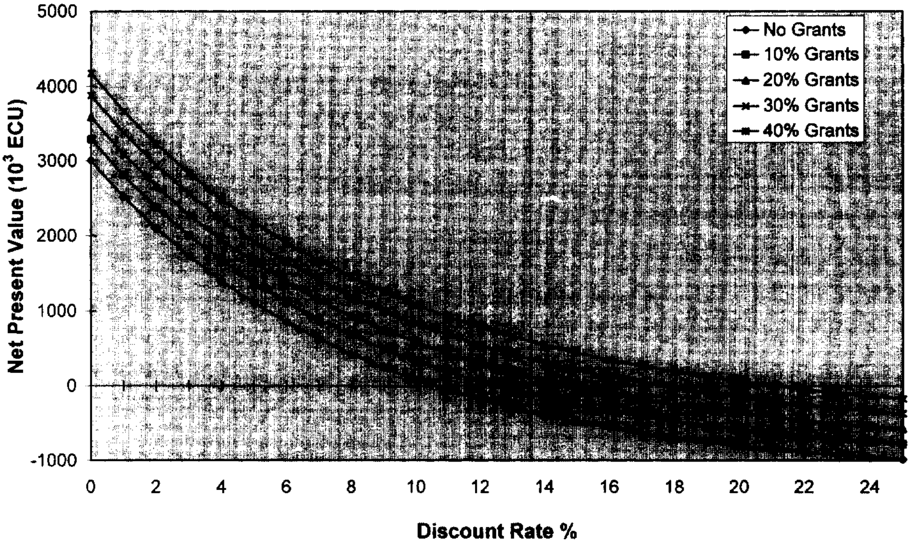

Fig. 8. Sensitivity analysis for grants percentage for the first scenario at Prinias site.

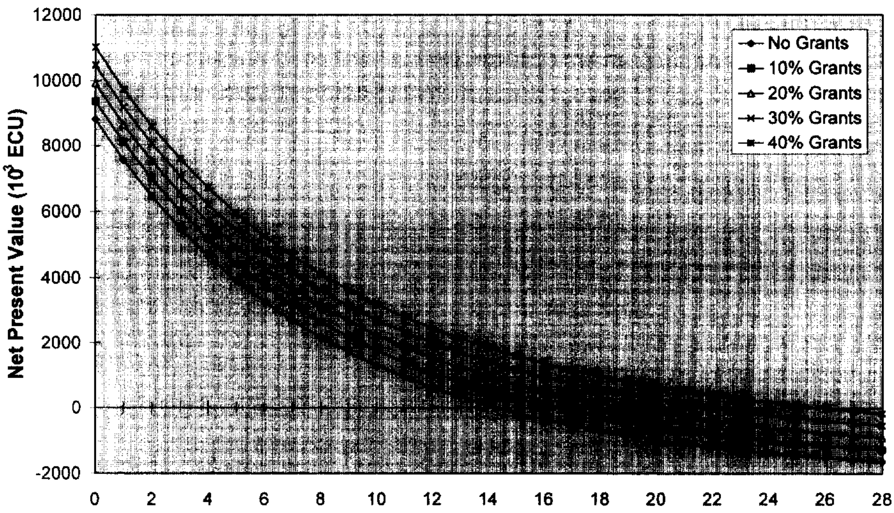

Fig. 9. Sensitivity analysis for grants percentage at Prinias site in the case of a longer high capacity line.

CONCLUSIONS

The proposed method aims at the evaluation of the geographical distribution of wind energy supply in a region and provides a new framework, for conversation among all parties involved in RES and energy planning.

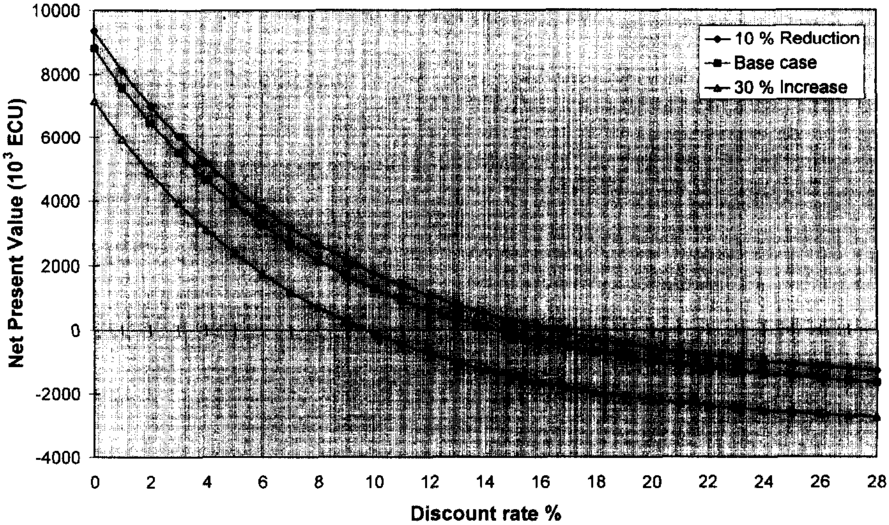

Fig. 10. Sensitivity analysis for the capital cost at Prinias site in the case of a longer high capacity line.

Analysis of the type presented in the present communication can provide invaluable help to the energy policy makers, the utilities, the local authorities as well as to private investors. All active energy actors can base their decisions on a critical evaluation of the regional, social and technological characteristics which influence the regional RES potential and economic expectations.

GIS is a useful tool providing the means for identifying and quantifying the effects of local constraints on the RES potential. In addition, it provides the flexibility to enrich the database, on which decisions are based, with spatial data providing additional RES availability restrictions, or non-spatial data providing other technology alternatives.

The financial framework for RES exploitation in autonomous systems, the inefficiency of the existing electricity grid and the high RES potential establish Crete as the ideal region for RES investments. In addition the active involvement of local authorities in the development of specific plants would increase the existing opportunities.

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