Powerful Planning

©2002 GETTY IMAGES, INC.

1540-7977/05/$20.00©2005 IEEE

Tools

GIS Power Up Distributed Generation

INDUSTRIAL AND TECHNOLOGICAL PROGRESS IS always related to an increase in energy consumption. This increase in electric energy demand must be met by enlarging the capacity of transmission and distribution networks and building new power plants. But, these improvements must also respect technical or environmental restrictions and pursue the best economic goals. In this sense, the construction of small- or medium-sized power plants near consumer locations will allow the minimization of losses in electric power networks and increase the efficiency of the overall energy system. These power plants, built by the utilities or by independent power producers (IPPs), are the main elements of the well-known distributed generation (DG).

Distributed generation offers a solution to the limitations in the capacity of distribution systems and, at the same time, improves the reliability of the overall power system by increasing its generation capacity reserves. Therefore, technical and economic factors have led to the expansion of DG. But this expansion can be limited by restrictions that depend on each location. In some geographical areas, a given environmental restriction can prevent the construction of some types of power plants while other geographical areas allow these same plants.

Distributed power generation in the form of conventional or renewable sources has increased during the last few years and will also increase in the near future.

The planning process to integrate dispersed generation in power networks must take into account multiple factors, such as the existing resources, the technology used in the generator, economic costs, the environmental impact, etc. Geographic

by Ignacio J. Ramírez-Rosado, L. Alfredo Fernández-Jiménez, Cláudio Monteiro, Vladimiro Miranda, Eduardo García-Garrido, and Pedro J. Zorzano-Santamaría

GIS allow the simultaneous evaluation of key technical, economic, and environmental factors.

information systems (GIS), software technologies developed for spatial data analysis, are suitable tools for solving these problems, and they allow the simultaneous evaluation of key technical, economic, and environmental factors. The development of new techniques under GIS platforms, such as geocomputational modeling, has increased the capabilities of GIS, allowing the systems to adapt to optimal DG planning studies. In various energy applications—from resource allocation to infrastructure planning—GIS have been used. Electric power applications have used GIS in energy planning, wind-energy evaluation, solar-energy and biomass resources, optimal siting of wind farms, and integration studies of these energy sources in remote areas.

Using adequate software under the GIS platform, users can obtain useful information on the economic or technical viability of any distributed power generation facility. Governments, environmental agencies, utilities, private investors, financial corporations, and local authorities can become users of these tools and active players in the field of distributed power generation planning.

DG Geoinformation Management

GIS are not only computer systems designed to produce maps but are also powerful tools of geographical analysis. GIS can be defined as integrated sets of hardware, software, databases, and processes designed to gather, preprocess, analyze, and visualize data able to be spatially located and related.

A main characteristic of GIS is the ability to handle information of very diverse origins and formats. Data can be in the form of maps, photographs, satellite images, tables, records, historical time series, etc., and these data relate to different areas in territorial arrangements, infrastructures, energy systems, environmental restrictions, and others.

GIS manipulate data in a digital model. Often it is necessary to gather these data and digitize them in the most appropriate model for GIS. These digital support models are the raster, the vector, and the surface data models.

The raster data model divides the studied area into a regular grid of cells where each cell contains a value and a geographical position. The contained value corresponds to a variable of interest. Each cell is georeferenced through a coordinate system: the cell size in real-world distance and the real-world location of the reference point of the whole grid. Each set of cells and their associated values constitute a layer; several layers can constitute a complete database, where each layer represents different variables (land use, elevation, solar radiation, etc.). The raster data model is the most suitable format for arithmetic operations among cells of the same layer or cells from different layers with the same geographical position. With raster analysis, a sequence of operations for a given location (e.g. photovoltaic systems sizing) can be extended to wider geographical regions by operating with maps instead of operating with variables of a single geographical location. Most GIS include modules to operate raster data models (such as surface analyses), obtain minimum cost paths, and perform arithmetic operations between layers.

The vector data model is used to store and manipulate well-defined graphical elements. These elements can be points, lines, polygons, etc. The attributes of these elements are stored in a database where users can associate the desired attributes. The vector data model is used to represent geographical elements like roads, electric networks, pipelines, contour lines, etc.

The third model, the surface data model, represents surfaces as a series of linked irregular triangles. The surface data model stores the topological relationships of these triangles. It is the most accurate format for the representation of surface shapes, particularly in the representation of digital elevation models, and allows the calculation of surface inclinations, angles of incidence, aspects, and flooded areas (in hydroelectric infrastructures).

Clearly, GIS offer a variety of structured data models suitable for the storage, manipulation, and analysis of the information needed in DG planning. Therefore, geographical regions can combine information on existing infrastructures (roads, power lines, etc.), renewable resources, and economic parameters in a single database with all the manipulation, visualization, and analysis features of these systems.

Figure 1 shows the composition of four layers in a GIS. The first and third layer are represented by the raster data model, where different cells can be observed. Each cell contains an associated value. The second layer is represented by a vector data model, where each point, line, or polygon can contain different attributes (numbers, strings, etc.) The bottom layer is represented by a surface data model, where the relief of the area can be seen. All the layers are reference the same geographical points.

Some renewable energy resources, such as solar radiation and wind power resources, can be efficiently stored in a raster data model, where the value of each cell represents the average solar radiation or mean wind speed for the area covered by the cell. Other data, such as roads to power net-

Geocomputation methods improve the planning process of distributed generation facilities.

works, can be stored both in a vector data model or in a raster data model. In Figure 1, the first layer represents the wind resources of the studied area, with higher values in the cells near the top of hills; the second layer represents the existing electric power distribution network with the possible connection points in black; and the third layer represents the land costs of the installation of a new DG facility.

The processing capabilities of GIS and the systems' ability to manipulate georeferenced data in different formats and models make them suitable for planning and optimal location of DG facilities. The raster data model allows the creation of different layers with useful terrain information on power systems planning. For example, it is possible to create a layer with the raster data model where each cell contains the average cost per meter of a new overhead electric line (that crosses the cell), and the GIS can calculate the corresponding economic cost of the electrical optimal path for the dc connection to the existing power network.

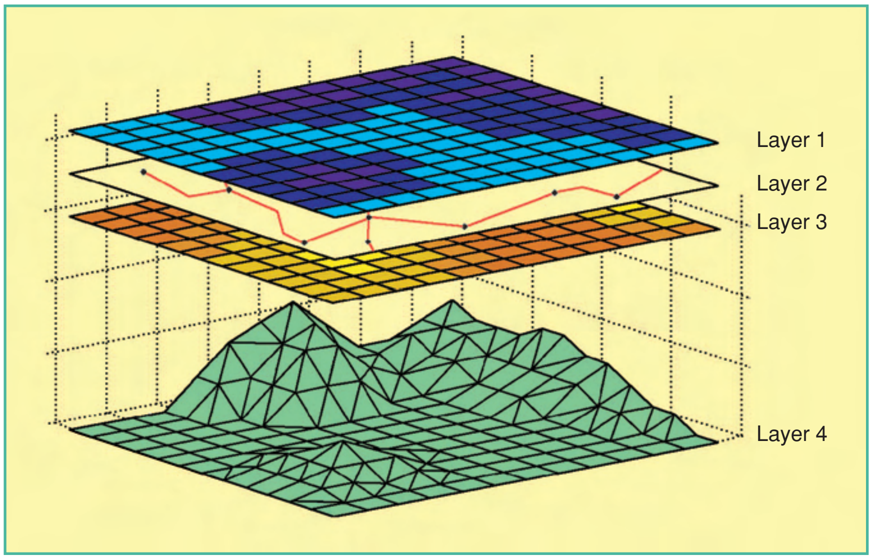

figure 1. Composition of four GIS layers. The first and third layers are represented by the raster data model, the second layer by the vector data model, and the bottom layer by a surface data model.

DG Geocomputation

The new techniques known as geocomputation increase the capabilities of GIS by integrating the ability to manipulate any kind of geographical data, modern computational methods, and high-level computing hardware. These techniques allow space-time systems to be created for process modeling and simulation, even in situations of uncertainty, nonlinearity, and discontinuity.

By means of geocomputation techniques, GIS can be adapted to the planning and performance evaluation of DG facilities. Geocomputation techniques can be programmed into the GIS software to calculate and analyze all the technical and economic aspects of DG and provide results for installation and maintenance costs, expected energy production and profits, or costs associated with the integration of these generators into existing power networks, among other technical and economic aspects.

DG facilities with a renewable resource can be isolated or connected to distribution networks. The rated power of an isolated DG can be calculated according to the quality of the existing resource in that location and the load demand. If the resource is variable, such as solar or wind resources, the capacity of storage systems can be estimated to be able to meet the load demand at all times. The rated power of a DG facility connected to distribution networks is calculated according to the existing resource and its distance to the loads or electric networks. Once the rated power has been estimated, GIS can be used to calculate the economic costs of the DG facility: costs of core and ancillary equipment, installation costs (according to the distance from roads, the nature of the terrain, and any other geographical factor that influences the installation costs), and operation and maintenance costs.

In order to determine the best possible DG alternative (considering economic factors), it is necessary to use comparable economic indicators. The most commonly used reference is the "levelized energy cost" (LEC), which calculates the economic cost of 1 kWh generated, including the equipment cost (annualized according to its service life), the operation and maintenance costs, and the possible costs of the energy resource used. Equipment costs must include, if necessary, land costs, the costs of new roads and paths for the installation of the equipment, and the costs of

GIS offer a variety of structured data models suitable for the storage, manipulation, and analysis of the information needed in DG planning.

the new electric power line connecting the equipment to the power network.

One of the most main features of GIS that can be applied to DG planning is the ability to make all the calculations described above, not only for a specific location, but for a whole geographical area. Thus, a suitable GIS software can determine the optimal location to build DG facilities with a given technology, i.e., photovoltaic or wind systems, by analyzing the LEC of all the geographical cells in the region. GIS has this ability to perform automatically massive calculations in hundreds of thousands of cells under the control of the distribution system planner. An example of this is the use of GIS in applications of spatial load forecasting that allow users to identify areas with a future increase in demand. Then, using a similar methodology, it would be possible to identify areas with an intensive future penetration of DG.

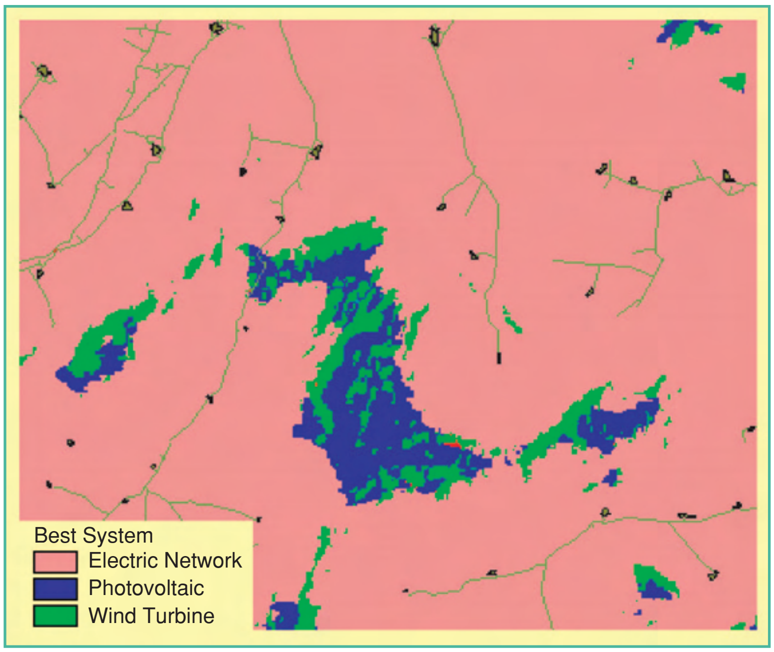

figure 2. A comparison of three technologies to meet (light) electric power demand in an area in the region of La Rioja (Spain).

One example of this calculation process is shown in Figure 2 (the studied region is an area of about 870 km^2 in La Rioja, Spain). The figure shows the results of a comparison of three technologies—wind turbines, photovoltaic systems, and distribution network expansion—for meeting light electric power demand in the region. Initially, a different scenario was prepared for each technology to obtain the LEC of those technologies in meeting a defined load. LEC results were stored in a raster data model with a cell size of 10^4m^2. Afterwards, the three LEC maps were compared, and the one with the lowest LEC was selected for each cell. The final results showed that areas near the existing distribution networks were most suitable for network expansion in order to meet the power demand; wind turbines or photovoltaic systems were more adequate in areas far away from distribution networks and with high-quality wind or photovoltaic resources.

The programming abilities of GIS allow users to include their own calculation models, algorithms, or simulation techniques. These computer features allow the inclusion of sophisticated models based on soft-computing techniques: fuzzy systems, neural networks, or evolutionary programming, which can expand the capability to process data while preserving the ability to display the results.

DG Geovisualization and Geoanalysis

One of the main characteristics of GIS is its capacity to present (to users) the data and the obtained results graphically. Users can quickly identify the geographical areas with the highest potential for DG without analyzing data tables.

One of the multiple applications of GIS in DG planning where the system can exploit its geographical manipulation ability is the calculation of DG equipment transportation costs: Figure 3 shows the LEC, calculated through GIS, for a diesel electric generator capable of feeding an isolated load with a peak power of 20 kW and a total yearly production of 35 MWh for Marajó Island, Brazil. The LEC includes equipment, transportation, installation costs, and operation and maintenance costs. On this island located in the Amazon region, rivers are the best means of transport; therefore, locations near rivers have lower LEC values than those at the island's interior. Locations near roads also have lower LEC values. The origin points of the equipment are located in the towns of Belém and Macapá, and the transportation costs

GIS can be used in DG planning to study negotiation processes among different energy actors to look for satisfactory geographical planning solutions.

include those derived from fluvial transportation, port unload, and transportation by road. Operation costs also include the distance to the fuel supply's origin. LEC isolines—or lines with the same levelized energy costs—are represented in dark blue.

The results can also be shown in statistical tables used for identifying the most relevant aspects of the planning problem under analysis or evaluating the part of the studied area where each DG technology is preferable under some selected criteria. Table 1 shows, in a numerical format, the statistical results for the scenario studied in Figure 2. The number of cells where each technology has the lowest LEC is shown in the column labeled "count." So, distribution network expansion is preferred in about eight 10^4 cells, a number greater than those obtained for photovoltaic systems or wind turbines. The minimum, maximum, range, mean, and variance of the LEC for each technology, all expressed in euros/kW (€/kW), are also represented in the Table 1 (at the moment of this research work, the value of €1 was approximately US$1).

Furthermore, GIS can be used in DG planning to study negotiation processes among different energy actors (with planning interests in conflict initially) to help them understand the point of view of the others and look for satisfactory geographical planning solutions for most of them. Figure 4 shows the results of a negotiation process between two groups (environmentalists and investors) trying to find possible locations for a new 10-MW wind farm in La Rioja, Spain. Both groups expressed in different maps (the two maps shown in the background of Figure 4) their tolerance index: a value from 0 to 1. These maps were stored in a raster data model where each cell contained the associated

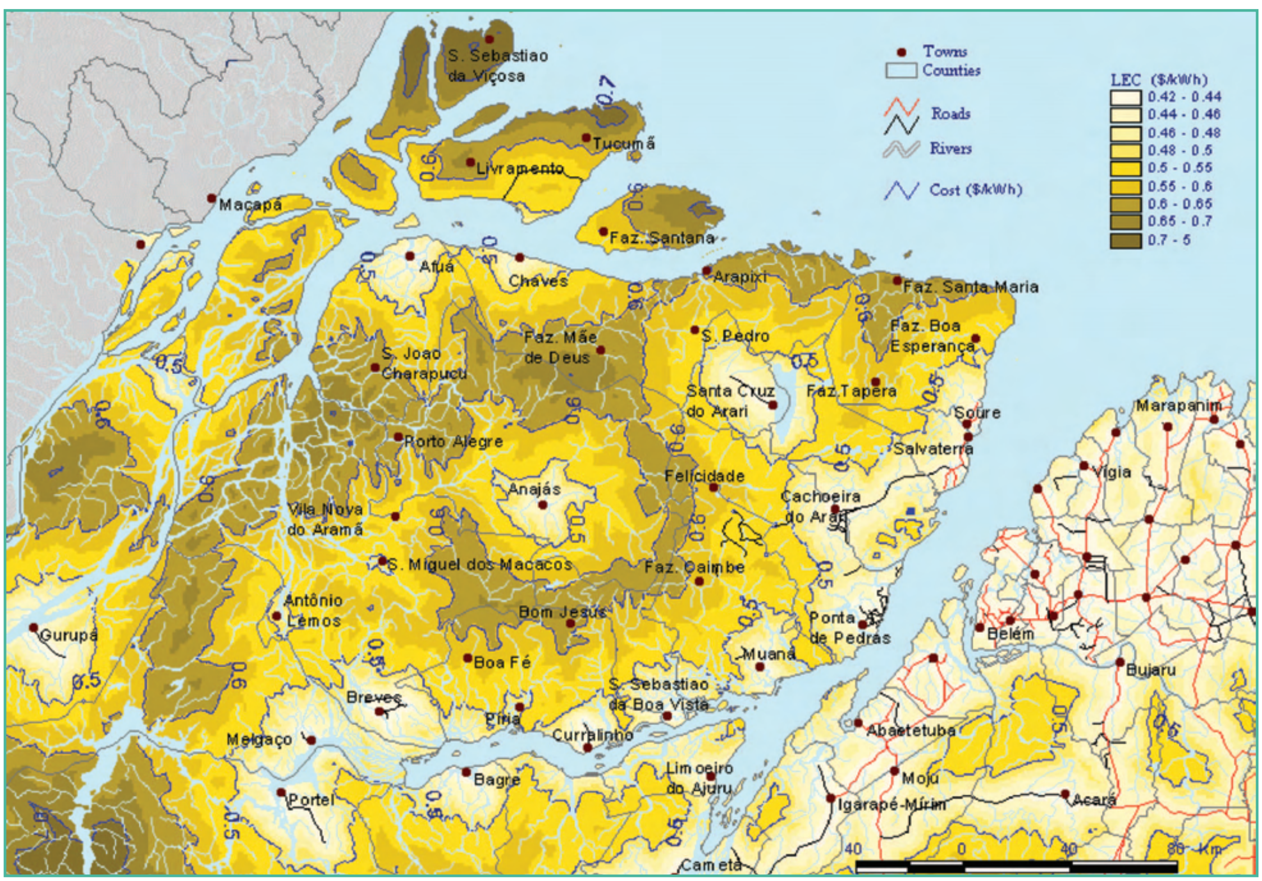

figure 3. LEC for a diesel electric generator capable of feeding an isolated load with a peak power of 20 kW in Marajó Island, State of Pará, Brazil.

table 1. Statistical results for the scenario studied in Figure 2.						
Label	Count	Minimum	Maximum	Range	Mean	Std
Network expansion	78,148	1.8402	8.7253	6.8851	5.6859	1.8887
Photovoltaic	4,381	3.1758	8.9414	5.7656	6.2298	1.4651
Wind turbine	4,035	1.7431	3.7277	1.9845	2.8344	0.4634

tolerance index. A low tolerance index implies a strong opposition, whereas a high tolerance index means a great interest (for investors) or weak opposition (for environmentalists). Obviously, environmentalists applied a low tolerance index to proposed sites at natural parks, protected areas, and villages and their surroundings. Investors applied a high tolerance index to the locations with a high LEC value. The final results were obtained by outranking all the cells considering the interests of both groups. The outranking process can be done by a simple comparison among cells or by applying complex techniques such as fuzzy sets. The results are shown in the central map of Figure 4, where the cells located in the outranking process are represented in different colors according to their position (cells with a better position are marked with the color representing number 9, and cells with a worse position are denoted by the color for number 1, although each individual cell contains its "position number").

DG planning (using GIS) can be applied to a whole region for an integrated regional energy planning by analyzing all the technical and economic variables of interest for that region with a powerful computational tool. Multiple scenarios with different economic or technical parameters can be simulated, which helps find the optimal planning solution. Graphical and/or statistical results from the calculation process are immediate, allowing strategic planning conclusions in an agile, visual. and global way with an analysis effort much lower than that required from other planning tools.

Agents in DG Planning Using GIS

Multiple agents are involved in the DG planning process and, therefore, authorities, utilities, and investors can become users of GIS for DG planning. Governments, as the main party responsible for power policy, are involved in the integration of renewable energy systems into national or regional power systems in order to guarantee sustainable development. Environmental agencies active in the defense of nature and the minimization of the damage caused by human activities can find in GIS a proper tool to analyze the environmental impact of DG facilities. Utilities more concerned with costs and

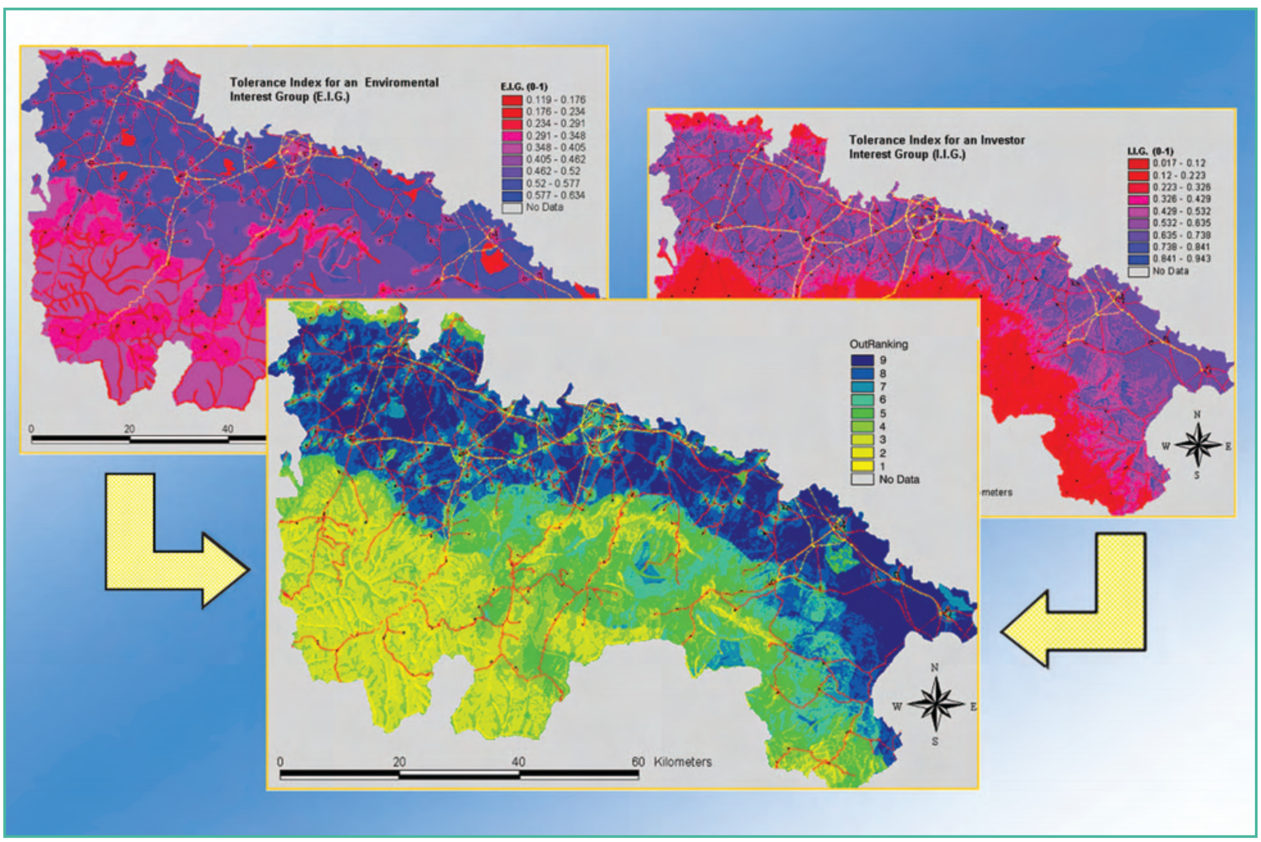

figure 4. Results of a negotiation process between two groups (environmentalists versus investors) for the installation of a new 10-MW wind farm in La Rioja, Spain.

meeting the power demand (also geographically dispersed) and, obviously, looking for the best economic investments, are also potential users of GIS. Other prospective users of GIS are private investors and financial companies interested in the profitability of distributed power generation. With GIS, manufacturers and distributors of DG equipment can identify areas having a high potential for promoting their products. Local authorities can also use GIS to increase the socioeconomic development of their area at the minimum political and social costs. Most of the time, these potential users will have to calculate some technical, economic, or environmental aspects of DG in a specific location, but at other times, they will be interested in evaluating a whole geographical area using GIS geoinformation, geocomputation, geovisualization and geoanalysis abilities for the optimal planning of DG facilities.

A promising new application of GIS to power systems planning is multiparty negotiation processes aimed at finding compromise solutions for groups with conflicting interests; for example, a given utility that wants to obtain the cheapest generation method and the environmentalists who try to minimize the environmental impact of new facilities. Obviously, the dialog and negotiation among different groups of interest will be straightforward if all these groups use the same GIS tools or even if they use the same GIS platform as a remote access server.

GIS and geocomputation methods have improved the planning and technical and economic evaluation of DG facilities. With adequate software, multiple actors might negotiate their interests in DG planning processes and will find in GIS a user-friendly tool that offers a direct interface with the different databases needed in planning processes and, above all, easily interpretable practical results with a minimal effort.

Acknowledgments

The authors would like to thank the Ministerio de Ciencia y Tecnología of Spain and the FEDER Fund (the European Regional Development Fund), and the Gobierno de La Rioja of Spain for supporting this research under Projects 2FD97-1514, DPI2001-2779-C02-02, and ANGI2004/02.

For Further Reading

Proc. IEEE, special issue "2001: An energy odyssey," vol. 89, Dec. 2001.

R.C. Dugan, T.E. McDermott, and G.J. Ball, "Planning for distributed generation," *IEEE Ind. Applicat. Mag.*, vol. 7, no. 2, pp. 80–88, Mar. 2001.

H.B. Puttgen, P.R. MacGregor, and F.C. Lambert, "Distributed generation: Semantic hype or the dawn of a new era?," *IEEE Power Energy Mag.*, vol. 1, no. 1, pp. 22–29, Jan. 2003.

M. Muselli, G. Notton, and A. Louche, "Computer-aided analysis of the integration of renewable-energy systems in remote areas using a geographical information system," *Applied Energy*, vol. 63, no. 3, pp. 141–160, 1999.

G.W. Ault, C.E.T. Foote, and J.R. McDonald, "Distribution System Planning in Focus," *IEEE Power Eng. Rev.*, vol. 22, no. 1, pp. 60–62, Jan. 2002.

GeoComputional Modelling. Techniques and Applications, M.M. Fischer and Y. Leung, Eds. Heidelberg, Germany: Springer-Verlag, 2001.

Biographies

Ignacio J. Ramírez-Rosado received his Ph.D. in electrical engineering from the Universidad de Zaragoza, Spain, in 1986, where he was Professor Titular de Universidad. In 1998, he moved to the University of La Rioja, Spain, where he is, at the present, full professor of the Department of Electrical Engineering. He has been responsible of several research projects in the power systems area, mainly in networks planning, load forecasting, and regional energy planning.

L. Alfredo Fernández-Jiménez received the electrical engineering degree from the Universidad de Zaragoza, Spain, in 1992. He is currently pursuing the Ph.D. degree at the Universidad de La Rioja, Logroño, Spain. His current interest is wind energy, load forecasting, and planning of power systems.

Cláudio Monteiro received his Licenciado, M.Sc., and Ph.D. degrees in electrical and computer engineering from the University of Porto, Portugal (FEUP) in 1993, 1996, and 2003. He is a researcher in the power systems unit of INESC Porto—Instituto de Engenharia de Sistamas e Computadores do Porto (Institute of Engineering in Systems and Computers of Porto), Portugal, working in the field of geographic information systems (GIS) applied to energy planning.

Vladimiro Miranda received his Licenciado, Ph.D., and Agregado degrees in electrical engineering from the University of Porto, Portugal (FEUP) in 1977, 1982, and 1991. In 1981 he joined FEUP and currently holds the position of Professor Catedrático. He is also the director of INESC Porto—Instituto de Engenharia de Sistamas e Computadores do Porto (Institute of Engineering in Systems and Computers of Porto), Portugal. He has authored many papers and been responsible for many projects in areas related to the application of computational intelligence in power systems.

Eduardo García-Garrido received the electrical engineering degree from the Universidad de Zaragoza, Spain, in 1996. He is currently pursuing the Ph.D. degree at the Universidad de La Rioja, Logroño, Spain. His current interest is distributed generation and planning of power systems.

Pedro J. Zorzano-Santamaría received the electrical engineering degree from the Universidad de Zaragoza, Spain, in 1990. He is currently developing research to obtain the Ph.D. degree at the Universidad de La Rioja, Logroño, Spain. His research interests include artificial intelligence techniques, electric power distribution planning, and geographical information systems.