APPLICATION OF GIS IN ENERGY–ENVIRONMENT MODELLING

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WORKING PAPER 91/8

SCHOOL OF GEOGRAPHY • UNIVERSITY OF LEEDS

"Application of GIS in energy-environment modelling"

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Working Paper 91/8

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1. Introduction.

Geographical Information Systems (GIS) have been used in the fields of ecology, earth sciences, geo-science and remote sensing for many years. Recently, social scientists have had their attention drawn to the fast-growing developments in GIS applications. Although there have been many discussions and evaluations of GIS applications in sciences and social sciences, there is little by way of review of the state-of-the-art of GIS, particularly in relation to energy-environment modelling and decision making.

The reason for this may be the absence of a unique definition of GIS within the field. The problem is further complicated by the existence of a great variety of GIS applications in the literature. Any computer software designed to handle spatial data for mapping or analytical purposes can literally be called a GIS application. In such circumstances, a comprehensive review of them all would not be possible, or necessarily desirable. Thus, the review of this paper is mainly confined to the state-of-the-art of "first-generation" GIS applications [1] which are basically oriented to maps. The recent development of analysis-based (or "second-generation") GIS applications to cope with specific requirements in particular fields (e.g. housing, health care, regional and town planning) is not included [2]. For convenience, the "first-generation" GIS is abbreviated as existing GIS applications below.

The primary objective of this paper is to examine the usefulness of existing GIS software for the field of energy studies. Discussion is based on two aspects: the theoretical-conceptual (e.g. issues of interests, methodologies) and the technical (e.g. program structure and system design). Strengths and weaknesses of existing GIS applications are explored with particular reference to the existing energy computer-aided models. Important insights and suggestions for further development are then portrayed.

2. An overview of "first-generation" GIS applications.

2.1 *Theoretical-conceptual aspects*

There are various definitions of Geographical Information Systems (GIS). Broadly speaking, as manifest in the existing available software (e.g. ARC/INFO [3], GRASS [4], CARP [5]), a GIS is a computerised database system for inputting, editing, coding, storing and retrieving information with reference to a geographical coordinate system or a set of places (i.e. spatial data). Conventionally, the initial concern of GIS was the combination and evaluation of different map overlays in order to provide additional (if not new) information to end-users about issues of interests. Later on, additional functions were added to GIS including the digital storage of map data, the production of maps and graphic displays, and the reporting of statistical summaries.

2.2 *Technical aspects.*

Application of GIS depends on two major components: computer hardware and computer software modules. Some applications work on a variety of hardware platforms [6], others on only a specific computer system [7]. However, there must be one or more input devices (e.g. digitiser, mouse, keyboard), one or more output devices (e.g. visual displays, printers, plotters), and some form of data storage (e.g. disk drive). A wide range of devices is required by each particular GIS software, though these are not taken as the major concern of this paper.

Turning to the application software, GIS is largely composed of five components:

(1) data input and edit
(2) data coding, storage and retrieval
(3) data output and presentation
(4) data transformations
(5) user-interfaces

The first component is usually presented to the end-users as an "editing environment" provided by the specific GIS application. This is done either by inputting from keyboard or digitiser. The second component is often handled by a "database management system" [8], the detailed operation of which is of little concern to the users. The third component projects a visually impressive representation of the input data to end-users via mappings and/or graphic displays. In some cases, statistical summaries are also given in conjunction with these visual representations by particular applications. The fourth component involves a huge array of programming algorithms that can be applied to transforming the input data in order to 'answer' the queries asked of GIS. In particular, stress is placed on converting a set of digitised map coordinates to machine readable formats which can be displayed on screen or drawn on paper. These data transformations include the storage of data for use in changing mapping scales, calculations of specific regional areas or perimeters, and imports and exports of the required data from and to third-party software, for example. Finally, the interactive environment provided by GIS to the end-users to activate various functions of the application software is the in-built "menu system" - an interface between users and the program components discussed above. Attached to the user-interfaces, there are a set of system warning, error detecting and data range checking sub-components.

In brief, GIS is a system (or set of programmed modules) integrating the technologies of relational database and graphical displays/packages.

3. State-of-the-art of existing computer-aided energy models.

3.1 *Theoretical-conceptual aspects.*

There is a great variety of energy-economic-environment models found in the field of energy studies, including input-output, econometric, systems dynamics, and linear programming energy models [9]. At present, there is no unique classification to categorise these energy models: each existing energy computer-aided model has been built by energy researchers to investigate their own specific energy issue(s). For instance, an energy model is specifically designed to examine changes of energy demand through a change in income or population patterns. Energy researchers formulate one (or more) energy problems and then build or find the similar tool(s) (e.g. energy models) to achieve their goals. This can be regarded as adopting the concept of a purposive-instrumental style of energy modelling approach [10].

Furthermore, each energy computer program is unique within the field in the sense that each model requires specific sets of data input to make it run. The 'composition' of the required datasets is entirely governed by the equations in chosen energy models. Energy modellers are interested in building, computing, testing and simulating a set of either pre-specified or user-defined energy equations. Results generated by the model run are used for analysis. In this case, energy models are mostly data-oriented and analytical-based applications.

3.2 *Technical aspects.*

Techniques adopted to tackle the specific energy issues vary from a purely conceptual (theory-building) to a highly technical (computerised) skill. Despite the differences in the energy problems addressed, only the applied and technical aspects of energy models formulated in the form of energy computer programs are considered in this paper.

Various applied computer-aided energy models can be found within the field, for example, IIASA's Energy System Program [11], U.N.'s ENERPLAN [12], and London Imperial College's ETB [13]. There is no uniform 'representation' of the programs for these energy computer models (i.e. the appearance and context of the software package). This is largely due to different specific needs and levels of programming techniques of the energy researchers.

In terms of programming structure, there is little difference between computer-aided energy models and GIS applications except that energy modelling packages are geared to model calculation and scenario simulation. Reports from the computer-aided energy programs are mainly in the form of tabular (e.g. spreadsheet) or graphical (e.g. line graph, bar chart) formats. In some cases, results can also be superimposed onto pre-digitised mapping areas in more sophisticated applications. Unlike GIS applications, digitising and mapping facilities are not the primary concern of the computer-aided energy models.

4. Intended uses of GIS in energy studies.

Despite the distinction between the mapping- and analytical-orientation, great similarities are found in both GIS and energy computer applications in terms of the composition of essential programming components. Learning from existing GIS applications, various aspects of energy-economic-environment modelling and planning decision making can be improved at different levels.

4.1 *Improved data structure and record formats.*

All first-generation GIS applications are mapping-oriented. Due to this, the main concern of the software is to digitise and record the detail of the physical landscape including the discrete features (e.g. bridges, roads, buildings) found on it. In this case, the recorded data can be massive. Yet, the input data is usually recorded in a specific way so that each dataset has a reference to another dataset. In so doing, it is easy and very efficient to find out the related datasets when a particular dataset is called for analysis. The kind of data records can be relational or hierarchical in structure for which many commercial database systems have been developed.

In the field of energy studies, energy and energy-related data are generally available from many international organisations (e.g. U.N., O.E.C.D) and the relevant national departments of specific interested countries. Despite the differences in level of detail, there is no uniform format and structure to record the data. It is commonly found that one dataset is incompatible with another from different source. Much time has to be spent by researchers in converting and compiling different sources of datasets to suit their needs.

If the original energy data could be put into a similar structure as used by GIS applications, the task of extracting and converting the data would be easier. Internal inconsistency and statistical differences due to the compilations of different sets of data from different sources are then minimised. Work in this area would build up an efficient databank. If these data structures were adhered to, and new data incorporated through time, then a useful set of data would always be available to energy modellers.

Furthermore, within this kind of data recording structure, simple statistical analyses and mathematical calculations can be pre-programmed and embedded within the database system. Simple energy questions such as changes in energy supplies and demands by type or percentage can be answered instantly without the need to run a separate model program. In fact, this helps energy researchers a lot as time-series analyses are frequently needed.

At present, facilities for importing and exporting recorded data in ready usable formats from one computer model to an another are often inadequate or completely absent. It is not uncommon for users to re-enter the required data, which can be very time-consuming. With the proposed data structure and record formats, the problem of data imports and exports is minimised.

4.2 *Adding spatial dimension to energy data.*

Energy-economic-environment modelling embodies a combination of social sciences and sciences. To a large extent, the available energy and energy-related data is quantified and recorded in relation to time with reference to particular countries. Within a country, more disaggregated energy data at provincial or county level is limited in supply. This is particularly true in the developing countries as most official statistical records are kept at national level. Without individual (private or commercial) efforts, disaggregated energy data cannot be found. Unfortunately, these energy records are not normally accessible by the public, which further restricts the comprehensiveness of energy studies.

GIS was originally developed from mapping techniques and cartography. With advances in digitising techniques and accuracy of map-scaling, tremendous mappings of, say, housing, commercial and industrial locations, and administrative territories are available via GIS applications for planning and decision-making purposes. For a long time, geologists have been applying GIS software to generate digitised maps, showing the structures and shapes of landscapes with reference to the available natural resources of an area. Besides relying on building and calculating energy models, awareness of energy problems or solution findings can be illuminated by mapping the changes of energy systems in relation to changes in the socio-economic-political environment of a society. In this case, GIS helps energy researchers to construct and record the spatial dimension of energy and energy-related data for further study.

4.3 *Helping site-specific energy resources analysis.*

With the outbreak of oil crises in 1970s and the gulf war in the early 1990s, greater attention has been paid to the studies of renewable resources as alternatives to the conventional fossil fuels.

The potential yield of renewable energy, such as water, wind power and biogas, is very site-specific and variable in time. For example, in case of water power [14], if a convenient site is not available on the stream itself, the usual practice is to divert some of upstream water, transport it along a channel or elevated conduit to another site, and then let it fall through a water wheel or stream. The amount of power obtained from a stream is proportional to the rate at which the water flows and the vertical distance which the water falls. Since stream flow varies by month and season, the pattern of availability of water power is space and time specific in the physical landscape of the studied region. For a long time, GIS applications have been used for landscape analysis (e.g. river and road diversions). With the availability of such site-specific GIS datasets, studies of the location and cost-effectiveness analysis of a particular renewable energy resource in a specific region would be helped.

4.4 *Increasing lobbying in energy policy and decision making.*

Energy strategic planning and decision making should not be restricted to the technicalities of building and testing energy models, but more importantly, to reviewing what the past was and what is really wanted for the future. Past data which can be found in statistical data books. Development of a better energy and energy-related database information system definitely contributes to the achievements of energy experts in tackling energy problems more efficiently in the future. At the same time, with the transformations of quantitative energy data and model results in the form of maps and graphs, the dissemination of information can be made more effective. The ability to display information in an easily understandable form (e.g. colour or pattern shading) means that even people without specific energy knowledge are enable to enquire about the present and future energy policies just by looking at the reports generated on screen. Owing to this, there is an increase in public enquiries and lobbying about energy policies, in particular the environmental issues (e.g. construct a nuclear power station).

5. Drawbacks of GIS applications.

Although the development of GIS applications provides a range of insights for the energy field, there are several limitations which to date hinder its full utilisation in energy computer-aid modelling approaches.

5.1 *Hunger for data.*

As mentioned previously, in order to develop a comprehensive, well-organised databank for use in energy models, a massive amount of energy and energy-related data input is required, in particular spatial data. Procedures and processes for collecting, compiling, converting and inputting relevant data from various sources prove to be extremely costly in terms of money, time and labour. It is far beyond the effort of an individual energy researcher. In addition, there is a relative lack of spatial data for energy analytical uses. The data hunger of existing GIS applications is the major drawback for use in energy studies. A purpose built energy computer-aided package would be comparatively less-demanding in data requirements, fulfilling the current needs of energy researchers.

5.2 *Difficulties in handling qualitative energy data.*

Given the present concern with environmental issues, strategic energy planning almost invariably involves consideration of a wide range of environmental factors in conjunction with monetary evaluations. For instance, qualitative data used in the studies of energy environmental risk perception and assessment are representations of personal attitudes, feelings or even cultural constraints. Although energy economists and environmentalists have recently been developing robust and practical methods for internalising environmental and other externalities into the energy planning and decision making processes, no consensus has yet been achieved as to how this should be done. Disputes in choosing appropriate methodologies and tools of analysis are inevitable within the field. More importantly, contents of the texts reviewed by the viewers are not normally recorded in the existing data record. They are usually generalised and quantified by energy researchers by means of a straightforward yes or no answer or a degree of percentile measurement (e.g. 20%, 40%, 60%, 80%, 100% dislike). In many cases, qualitative statements and text is available (e.g. from questionnaires) but is not entered into the system. It would be an easy step to include such information, in the form of a free text field in the data structure. This extra qualitative information could be made available to the researcher on demand, enabling further decisions to be made.

GIS applications are heavily based on processing quantitative data. Recorded data are mostly in the form of relational or hierarchical structures. Pure text or flat format data input is rare in GIS applications, but would seem to be the best representation of the qualitative energy data. In this respect, these required data record structures must be included in the future developments of GIS in order to be of great value to energy environmental analyses.

5.3 *Lack of modelling oriented modules.*

Mapping and graphical techniques are substantial in GIS applications, but the essential elements of analytical and modelling facilities found in computer-aided energy models are lacking. Routines such as inputting, evaluating and calculating energy model equations and expressions are normally unavailable. This limits the utilisation of GIS applications within the field of energy modelling.

5.4 *Absence of sophisticated analytical tools.*

Apart from providing simple statistical summaries, more sophisticated analytical tools such as time-series multivariate regression analysis, factor analysis, multi-criteria analysis are missing in most existing GIS applications. These analytical tools are essential to energy researchers for building and testing different types of energy models. Software like SPSS [15] and SAS [16] have been used by energy researchers for many years to achieve these goals. The absence of sophisticated statistical and mathematical analytical modules severely diminishes the degree of usefulness of existing GIS application in energy analysis.

5.5 *Missing decision support or expert systems.*

Recent energy computer-aided models rely on developing an intelligent, sophisticated decision support or expert system, to help strategic energy policy planning and making. In many cases there is a need to ask "what if" types of question. Most GIS are able to produce results whether or not the input is reasonable. The user gains no guidance from the GIS in attempting to come to an optimal result. Techniques in decision support and expert systems have been improved over the past few years, but as yet there is a shortage of these required functions in existing GIS applications.

5.6 *Incompatibility of one GIS applications to an another.*

Although most GIS applications possess rather sophisticated in-built data transformation routines, problems of incompatibility of data imports and exports are encountered. Rather than helping to solve the problem of inconsistency of internal energy data, GIS applications create a further type of spatial data problem.

5.7 *Elicitation of knowledge and energy theory seeking.*

Despite advances in GIS development, each software package is restricted to its own pre-defined functions. Apparently, there is no error-free or fool-proof program. Improvements of future GIS applications rely entirely on advances in computer- and programming-technology rather than conceptual-theory building. The creation of menus, database, drawing, plotting, calculation, reporting and decision supporting modules is geared towards knowledge of computer science. An intimate relationship between GIS and computer science can be seen. Yet, it is worth asking whether future energy researchers should have to acquire these computer skills as a priority. If so, the process of theory or knowledge seeking would seem to be overwhelmed by the technical aspect of any proposed energy computer-aided model in the future.

5.8 *Requirements of intensive training and expert support.*

GIS applications are not easy to use without any proper training or expert advice. The processes of data input, compilation, transformations and generating reports requires a high level of technical training and institutional organisation if it is to be done efficiently. In this respect, costs of labour, equipment and time involved are substantially high, making GIS an expensive planning tool.

On the other hand, most available stand-alone energy computer-aided models are comparatively cheap to buy and to run. Most of them run on personal computers. At the same time, energy computer programs are rather simple and easy to use. They enjoy a high degree of user-friendliness. Furthermore, the existing energy programs are specifically built to fulfil certain purposes, say, to evaluate changes in energy systems for a certain period of time. A good energy computer program often provides sufficient guidance and information to the end-users. With a prior knowledge of energy, users can manage to use the program on their own and in a short period of time, productive model results can be generated.

5.9 *Problems of bureaucratic or institutional constraints.*

As numerous energy models are found within the field, there is no shortage of computer-aided energy models and skills to aid energy-economic-environmental planning and decision planning. Problems encountered are not purely technical but are largely imposed by the structure of bureaucracy and the institutional context of an organisation, and its political ideology. Advances in GIS might offer valuable contributions to strategic energy planning or theory building, but at the same time, there is a risk that it would be used intentionally as a superficial means to assure the public credibility of pre-chosen policies, through a process of mystification.

5.10 *Inappropriate technology for the developing countries.*

GIS cannot be regarded as an appropriate technology applied for developing countries for energy policy making or assessment. Research findings from authors such as Dickinson and Calkins (1988) and Yapa (1991) also suggest that GIS applications are costly in terms of hardware and software requirements. Strict legal restrictions are normally imposed to the use of those GIS applications to protect copyright. Furthermore, there is a severe lack of 'local' expertise to support the software in developing countries. A long training session for staff is needed before the software can be used efficiently. Thus, a hasty acceptance of existing GIS applications for use in energy-environment-economic planning and decision making means a reduction of the level of self-dependency of the third world countries. It is preferable to import knowledge than to sell 'technical' products from the West to the East.

6. Conclusions.

The current development of GIS applications offer significant insights and technical aspects to improve the present state-of-the-art of existing energy computer-aided modelling programs (such as data structure and records, mapping and graphic displays). Despite inherent limitations of the software design, present GIS technology cannot be fully adopted for use in energy modelling, strategic energy decision making and planning. Considerations to be taken into account are the massive hunger for fully integrated spatial and economic energy and energy-related data, the absence of sophisticated analytical (mathematical and statistical) computer modules, deficiencies in intelligent, expert support and information systems, and so forth. In addition, economic evaluation of the implementation of a GIS also proves extreme costly in terms of time, labour and capital (e.g. computer equipment and costs in Research & Development). Furthermore, lack of local expertise and practical skills severely hinder the effectiveness of utilising the existing GIS applications in the Third World for use in energy studies.

Finally, it is realised that advances in GIS largely rely on improvements in (computer) technicalities rather than theory- or knowledge-seeking. According to Siu (1989), the problem of fragmentation in theory and model building is found within the field. The diversifications of adopted methodologies and (computer) tools for use in energy strategic planning and decision making is deemed to be unavoidable. The greatest concern of energy-environment-economic studies is the need for a strong, conceptually sound theory with technical and pragmatic strengths to solve the problems of diversification and fragmentation. Without further refinement and modification of first generation GIS, great contributions towards energy studies will not be achievable.

Footnotes

[1] Since there is no unique definition or classification, the categories "first-" and "second-generation" are adopted by the author to distinguish between the map-oriented and analysis-based GIS applications. Early GIS applications were initially developed to handle and process spatial data for mapping purposes. Current GIS applications often built with statistical and mathematical analysis in conjunction with mapping facilities. They are geared to analysis-based applications.

[2] A paper discussing the potential and intended uses of the "second-generation" GIS applications in energy studies will be presented in due course.

[3] ARC/INFO is copyright of Environmental Systems Research Institute (ESRI). Basically, ARC/INFO consists of two sub-systems:
(a) ARC - a set of programs for the management of locational coordinates or geographical features (e.g. points, polygons and lines) which are stored and processed in vector format.
(b) INFO - a set of programs to handle the thematic data processing. It is a relational database system which is a commercial software that has been linked to the map editor ARC.

[4] GRASS (Geographical Resources Analysis Support System) is a public domain GIS software developed by SCS.

[5] CARP (Computer Assisted Regional Planning) was developed at the Pennsylvania State University as a low-cost computer mapping and planning tools. It has the capability for use in the regional planning offices of the Third World by linking locally-available popular software.

[6] Variants of ARC/INFO are available to run on a Sun Workstations, DEC VAX systems, and on IBM PC or compatible systems.

[7] For instance, GAIA (Geographic Access Information and Analysis) is a software program for the colour Macintosh platform designed to display, manipulate, and analyse digital earth imagery (e.g. satellite images). Further queries should put forward to Richard Podolsky, GAIA Project Leader, 300 w. 23rd St. 10D, NY, NY 10011.

[8] Basically, there are four types of database systems: flat form, relational, hierarchical and free text. The commonly used database systems are more often the relational type (e.g. dBase, Paradox, FoxPro and DataEase).

[9] A substantial literature is found on the energy modelling approaches mentioned. For illustrative purpose, only a few are cited below:
(1) Input-Output energy model:
The demand driven I-O energy model developed by

Common and McPherson (1982).
The supply driven I-O energy model introduced by Giarratani (1976).
The dynamic I-O energy model discussed by Hoffman and Jarass (1982).

(2) Econometric energy model:
Single-equation econometric energy models were discussed by Smil & Kuz (1976), and Pearce & Westoby (1984).

(3) Systems dynamics energy model:
Systems dynamics energy-demand model developed by Allen et.al. (1984).

(4) Linear programming energy model:
Linear programming energy model developed by Muller (1979).

[10] Discussion of the theory of purposive-instrumental rationalisation can be found in Siu (1989:3-5,233-271).

[11] The International Institute for Applied Systems Analysis's Energy System Program (IIASA's ESP) was an international energy study, under the leadership of W. Hafele, concentrated on global aspects of the long-term (from 1980 to 2030) transition from the present energy system based on cheap fossil fuels to one which may be more sustainable. The whole computer program comprises of three major interconnected modules:
(a) The MEDEE-2 (Module d'Evolution de la Demand d'Energie) - for energy demand forecasting
(b) The MESSAGE - for energy supply prediction
(c) The IMPACT - for the overall economic assessment

[12] ENERPLAN is a micro-computer program designed to be used by energy planners in developing countries. It was developed by the Tokyo Energy Analysis Group in 1985, under the auspices of the Department of Technical Cooperation for Development of the United Nations.

[13] Energy Tool Box (ETB) is an energy modelling package developed at Imperial College, London, in late 1990.

[14] The use of water power is restricted by the availability of a stream water. In addition, the capability of a specific stream water to generate usable energy depends on two factors: the velocity of water (i.e. the kinetic energy) and the difference in elevations between two sites (i.e. the potential energy).

[15] SPSS (Statistical Package for Social Scientists) is a registered trademark of SPSS Inc. Various SPSS software run in different computers have been used by energy researchers such as SPSSx on mainframe, SPSS/PC on personal computers.

[16] SAS (Small Area Statistics) is a registered trademark of SAS Corporation.

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