Jul 1st, 12:00 AM

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Spatio-temporal Analysis of Decentralized Energy Systems

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Abstract: GIS can not only improve the way we produce and deliver energy, but can also change the way we view our earth’s resources. In order to provide sustainable energy supplies, humankind is exerting tremendous efforts to secure and cultivate renewable resources, such as wind, solar, geothermal, and biomass energy resources. Using local resources reduces disparity in rural and remote areas in terms of the reliability of supplies and promotes the generation of income. In this research, spatio-temporal analysis in GIS is employed to design decentralized energy systems using renewable energy resources. Spatio-temporal analysis entails estimation and visualization of renewable energy sources on regional and local spatial scales, and optionally in separate periods. GIS organizes spatial data so that case-oriented optimization methods can select the data necessary for specific tasks. Thematic maps are used for data inputs and display of original data and optimization outputs. In addition to spatial methods in GIS, advanced workflows based on linear programming are developed to extend standard routines. Spatio-temporal analysis is employed to design a decentralized system in a selected region of the Czech Republic. The resulting design includes biomass technology, wind turbines, and solar energy systems. The results yield various scenarios based on setting different cost coefficients and constraints. In addition to traditional constraints, such as available land and funds, local restrictions and regional regulations are used to demonstrate other limits that can significantly change the technological and economical parameters. The final map layers can illustrate the total utilization of various energy systems in space and time, which can assist in decision-making processes on local and regional scales.

Keywords: Decentralized energy; linear programming; energy optimization; GIS.

1. INTRODUCTION

World energy consumption has become one of the major issues discussed worldwide at the beginning of the new millennium. Energy security, renewable energies and energy efficiency are now considered to be top priorities to be addressed by most governments. In developed countries, the global financial crisis has opened the way for renewed recovery policies focusing on reducing energy dependency through increasing the use of renewable and sustainable energy sources. Effective joint implementation strategies have emerged from the European Union (EU) countries and the USA addressing very strictly defined and demanding goals for gradual fulfillment in the years to come. Thus, a number of technological innovations have emerged and a strong impulse occurred towards the application of new energy systems and new investments in clean energy technologies. The development of integrated energy systems, capable of delivering sustainable electricity and other energy sources to local populations and of working as a backup in the distribution network, is emerging as a viable approach for dealing effectively with the above-mentioned new set of global problems. The current energy systems should be analysed by new tools to optimize planning and analysis on different scales in order to compare the wide range of influences exerted at
local, regional and global levels [Mendes et al., in press; Patitzianas and Karagounis, 2011].

1.1 Energy models

Originally in developed countries and now in developing countries, the statistical data reflect a high dependency on traditional sources of energy, which causes negative impacts related to rapid deforestation and other related phenomena. The phenomenal growth in population and the constantly improving quality of life have led to steadily increasing energy consumption over the past few decades. These needs can no longer be met by traditional inefficient energy technology using a central predominant resource and only a few local resources. After the oil crunch of the seventies, planners had to revise their energy models and predictions in order to develop efficient energy planning and optimization of a wider range of potential energy sources. The experience in developing countries over the past years has shown that decentralized energy technologies based on local resources can be alternatives to centralized commercial sources of energy.

Many integrated energy models linking both commercial and renewable energy sources have been developed over the past few decades [Swan and Ugursal, 2009; Jebaraj and Iniyan, 2006]. The models can help to allocate potential local renewable energy sources, such as bioenergy, solar, wind and small hydropower sources in order to achieve desired result of meeting future energy demands. New trends in energy modelling are supported by improved technologies of waste recycling and by introduction of renewable energy sources. Various types of energy models, such as planning models, energy supply-demand models, emission reduction models, and optimization models are complemented by renewable energy sources.

Primarily, solar, wind and biomass are accepted as widely available renewable energy sources. Solar energy modelling is mostly focused on prediction of energy amounts in dependence on location and meteorological conditions in urban or rural environments [Gennusa et al., in press; Janke, 2010]. In many countries, wind energy has been proven a cost-effective energy source over the past decade. This is a result of technological improvements that offer an attractive complement to conventional power generation technologies [Bishop and Stock, 2010; Haaren and Fthenakis, 2011; Ouammi et al., 2012]. Based on Directive 2001/77/CE of September 2001, the Council of Europe approved rules on the promotion of electricity generated using renewable sources of energy. In order to achieve optimal use of agricultural and forest residue biomass, models have been developed to resolve transport strategies that can be used in relation to a network of bioenergy products around an area of interest [Perpiñá et al., 2009].

A number of model techniques are used to resolve and optimize the utilization of energy. Energy planning models are mostly based on statistical methods and multi-objective programming techniques associated with dynamic programming. Energy supply-demand models use linear multiple regression techniques. Optimization models are based on methods of operational research, such as linear programming. Other techniques incorporated in models include neural network and fuzzy theory.

2. SPATIO-TEMPORAL ANALYSIS WITH GIS

Making decisions on energy systems can be improved by including topological analysis in energy models. This can be managed by Geographic Information Systems (GIS) that organize data into map layers extended by tables of contents [Zeiler, 2010]. The ability to process geographic data from a variety of sources and integrate them into a mapping project provides energy models with a means of viewing the Earth’s resources [Maguire et al., 2005; Goodchild et al., 1996]. In the past, GIS has often been used with case-oriented software tools for spatial data
management, 3D modelling, spatial analysis, and network analysis. With the increasing power of GIS hardware and software, this relationship is being reconsidered and GIS development tools offer direct integration of numerical modelling into the GIS data. Thus, energy models can extend existing GIS capabilities and utilize its extensive set of methods and functions [Matejicek, 2011; Lahdelma, 2003]. In spatio-temporal analysis, GIS can determine, for example, the most favourable locations for renewable energy sources in dependence on terrain data, meteorological data, profits for energy consumers and the impacts on the local community.

### 2.1 Optimization of energy sources by linear programming

In order to optimize decentralized energy sources, an operational research method, linear programming [Bazaraa et al., 2011; Lahdelma and Hakonen, 2003], can be used to maximize energy production in the framework of required constraints in the selected area. The criterion function to be minimized is:

\[ c_1x_1 + c_2x_2 + \cdots + c_nx_n, \]

where the \( c_1, \ c_2, \ldots, \ c_n \) are the cost coefficients for each type of unit energy and the decision variables represent the amount of energy per time unit. The inequality:

\[ \sum_{j=1}^n a_{ij}x_j \leq b_i \quad \text{for } x_j \geq 0 \quad i = 1, \ldots, m, \quad j = 1, \ldots, n, \]

where the coefficient \( a_{ij} \) forms the constraint matrix that can be represented by limited land area, funds, restrictions imposed by the local inhabitants and state regulations. Coefficient \( b_i \) represents the availability. A set of values of variables \( x_1, \ldots, x_n \) satisfying all the constraints forms a feasible solution.

The linear programming method is applied to the sample region under consideration corresponding to about 2000 km\(^2\) in Figure 1. The map schema is complemented by the road, rail and river networks. The regional settlement is represented by a point layer. The biomass plant is located in a central part of the region. The basic classification of land cover (urban zone, agricultural area, forest and water) is illustrated in the background layer. The real image of the region draped over the digital terrain model with a vertical scale factor of 3x is depicted in Figure 2. For each rectangle with an area of 1 km\(^2\) of a regular grid overlap, the maximum available energy production, local funds, restrictions of the local inhabitants and state regulations are estimated approximately in dependence on the available data, such as the map of biomass sources, the regional wind map, the map of solar sources and information about local development, Figure 3. For biomass energy sources, it includes local production and transport costs to the biomass plant. For solar and wind energy sources, it covers the overhead and local operational expenses. The electricity and heat that come from central energy systems are represented by uniform operational expenses for the whole grid in the region.

The criterion function for the local area \( k \) in the grid layer is:

\[ c_{bio}x_{bio} + c_{wind}x_{wind} + c_{solar}x_{solar} = \max, \]

where \( c_{bio}, c_{wind} \) and \( c_{solar} \) are the cost coefficients for each type of unit energy, such as energy from biomass production \( x_{bio} \), wind energy sources \( x_{wind} \) and solar energy sources \( x_{solar} \). Limited energy production, funds, restrictions imposed by the local inhabitants and state regulations are represented by inequalities:

\[
\begin{align*}
    a_{bio,land}x_{bio} + a_{wind,land}x_{wind} + a_{solar,land}x_{solar} & \leq b_{land} \\
    a_{bio,funds}x_{bio} + a_{wind,funds}x_{wind} + a_{solar,funds}x_{solar} & \leq b_{funds} \\
    a_{bio,rest}x_{bio} + a_{wind,rest}x_{wind} + a_{solar,rest}x_{solar} & \leq b_{rest} \\
    a_{bio,reg}x_{bio} + a_{wind,reg}x_{wind} + a_{solar,reg}x_{solar} & \leq b_{reg} \\
    x_{bio} & \geq 0; \ x_{wind} & \geq 0; \ x_{solar} & \geq 0
\end{align*}
\]
where \( a_{\text{bio,land}} \), \( a_{\text{wind,land}} \) and \( a_{\text{solar,land}} \) are the coefficients from the constraint matrix focused on land limits. \( a_{\text{bio,funds}} \), \( a_{\text{wind,funds}} \) and \( a_{\text{solar,funds}} \) are the cost coefficients focused on limited funds. \( a_{\text{bio,rest}} \), \( a_{\text{wind,rest}} \), \( a_{\text{solar,rest}} \) and \( a_{\text{bio,reg}, \text{wind,reg}} \), \( a_{\text{solar,reg}} \) are the coefficients focused on potential local restriction for renewable energy sources, and state regulations for renewable energy sources, respectively. \( b_{\text{land}}, b_{\text{funds}}, b_{\text{rest}} \) and \( b_{\text{reg}} \) represent the total land capacity, total funds, aggregated local restriction for renewable energy sources and aggregated state regulations for renewable energy sources in rectangle \( k \).

Figure 1. The sample region under consideration complemented by the road, rail and river networks, by the regional settlement and by the biomass plant located in a central part. The basic classification of land cover is in the background layer.

Figure 2. The real image of the region draped over the digital terrain model with vertical scale factor of 3x.
3. NUMERICAL MODEL FOR SPATIO-TEMPORAL OPTIMIZATION

Optimization of decentralized energy sources is solved for each rectangular area of 1 x 1 km, Figure 4. The solution uses the Simplex algorithm [Dantzing, 1947] implemented in the 'linprog' package by Henningsen [2012] in the framework of the R project for statistical computing. As an example, the subarea of interest is optimized in the framework of the sample region under consideration, Figure 5. Two scenarios are introduced in dependence on the cost coefficient of solar energy (1.scenario: $c_{\text{solar}}=5500$; 2.scenario: $c_{\text{solar}}=550$).
Figure 4. Local biomass, solar and wind energy sources that generate energy production in local area $k$ in the grid layer.

Figure 5. Local biomass, solar and wind energy sources, the selected rectangle $1 \times 1$ km is used to demonstrate spatio-temporal analysis and optimization.

The numerical model for optimization by linear programming complemented by a feasible region of solution (Figure 6) of the criterion functions:

1. scenario: $4580x_{bio} + 2230x_{wind} + 5500x_{solar} = max$,  
2. scenario: $4580x_{bio} + 2230x_{wind} + 550x_{solar} = max$,  

$$0.25x_{bio} + 0.33x_{wind} + 0.20x_{solar} \leq b_{land}$$
$$0.33x_{bio} + 0.20x_{wind} + 0.20x_{solar} \leq b_{funds}$$
$$0.33x_{bio} + 0.50x_{wind} + 0.17x_{solar} \leq b_{rest}$$
$$0.50x_{bio} + 0.17x_{wind} + 0.14x_{solar} \leq b_{reg}$$
$$x_{bio} \geq 0; x_{wind} \geq 0; x_{solar} \geq 0$$

The maximum value of the criterion function for the 1st scenario is:

\[4580x_{\text{bio}} + 2230x_{\text{wind}} + 5500x_{\text{solar}} = 4580 \cdot 0 + 2230 \cdot 0 + 5500 \cdot 5.00 = 27500\]

The maximum value of the criterion function for the 2nd scenario is:

\[4580x_{\text{bio}} + 2230x_{\text{wind}} + 550x_{\text{solar}} = 4580 \cdot 1.70 + 2230 \cdot 0.88 + 5500 \cdot 0 = 9749\]

The calculation demonstrates the different strategy of utilization of local renewable energy sources in dependence on a change in the cost coefficient for solar systems. For a significant reduction in the costs of solar systems, another strategy based on biomass and wind energy is recommended by the linear programming method.

4. CONCLUSIONS AND RECOMMENDATIONS

The paper shows the utilization of renewable energy sources on regional and local scales. A number of models are described in the introduction in order to provide proper selection. Finally, the GIS technology is used for spatio-temporal analysis in order to estimate the potential energy sources. A region of about 2000 km² is divided into rectangles (1 km²) to show the partial optimization in the context of the selected rectangle. Two scenarios and sample coefficients demonstrate various strategies for utilization of the renewable local energy sources. The local calculations can be implemented for the whole region and for several periods corresponding to temporal changes in the model parameters, such as cost coefficients, funds, local restrictions, and regional regulations. The final map layers can illustrate the total utilization of various energy systems in space and time, which can assist in decision-making processes on local and regional scales. In addition to traditional constraints, such as available land and funds, local restrictions and regional regulations are used to demonstrate other limits that can significantly change the technological and economic parameters.

In order to put the presented algorithm into practice, the cost coefficients in the 1st scenario originate from national regulations. The coefficients in the constraint...
matrix are derived from spatio-temporal analysis (estimated capacities of energy sources), and from expected local and state preferences (funds, local restrictions, and state regulations).

ACKNOWLEDGMENTS

This study was supported by the GIS Laboratory, Charles University in Prague in the framework of research activities focused on relationships between energy, nature and society.

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