Simulation Tools for the Exploitation of Renewable Energy in the Built Environment: The EnTrack-GIS System

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ABSTRACT

In many countries there is an abundance of renewable energy (RE), from a variety of sources. Each source has its own characteristics, and presents its own problems of matching to consumer demands, and of integration with existing sources of energy supply. This paper reports the outcome of a project [1] concerned with the development of a RE decision support tool to facilitate large-scale (e.g. city-wide) fuel consumption monitoring and the setting of realistic targets for energy use. Crucially, the tool incorporates simulation methods for the prediction of building energy demand and RE installation capacity for entities which are outwith a monitoring scheme.

The paper describes the project's outcome in relation to the inter-related issues of *strategic planning* and *building design intervention*, with the emphasis throughout on the role of simulation for building and renewable energy scheme appraisal. Specific approaches to the modelling of wind turbine power production and building electrical power consumption are described.

Keywords: energy management, buildings, renewable energy, simulation, virtual metering.

INTRODUCTION

Against the contention that, to be effectively applied, simulation must be placed within a general energy management framework, the EnTrack-GIS system has been devised as illustrated in Figure 1. Essentially, the system comprises a fuel information management module, EnTrack [2], linked to a Geographical Information System (GIS) [3]. The EnTrack module supports the storage and analysis of historical fuel consumption data and offers simulation capabilities for detailed RE scheme and building assessments. The GIS module supplies scoping data to EnTrack in support of these assessments and receives back the results for display alongside other relevant geographical data types (such as land designation or individual RE scheme/building locations).

The system's rationale is that renewable energy technologies can best be promoted by:

a) supplying planning and energy management personnel with information describing the spatial and temporal aspects of local demand patterns and supply potentials;

b) and supplying building designers with the means to assess the viability of autonomous

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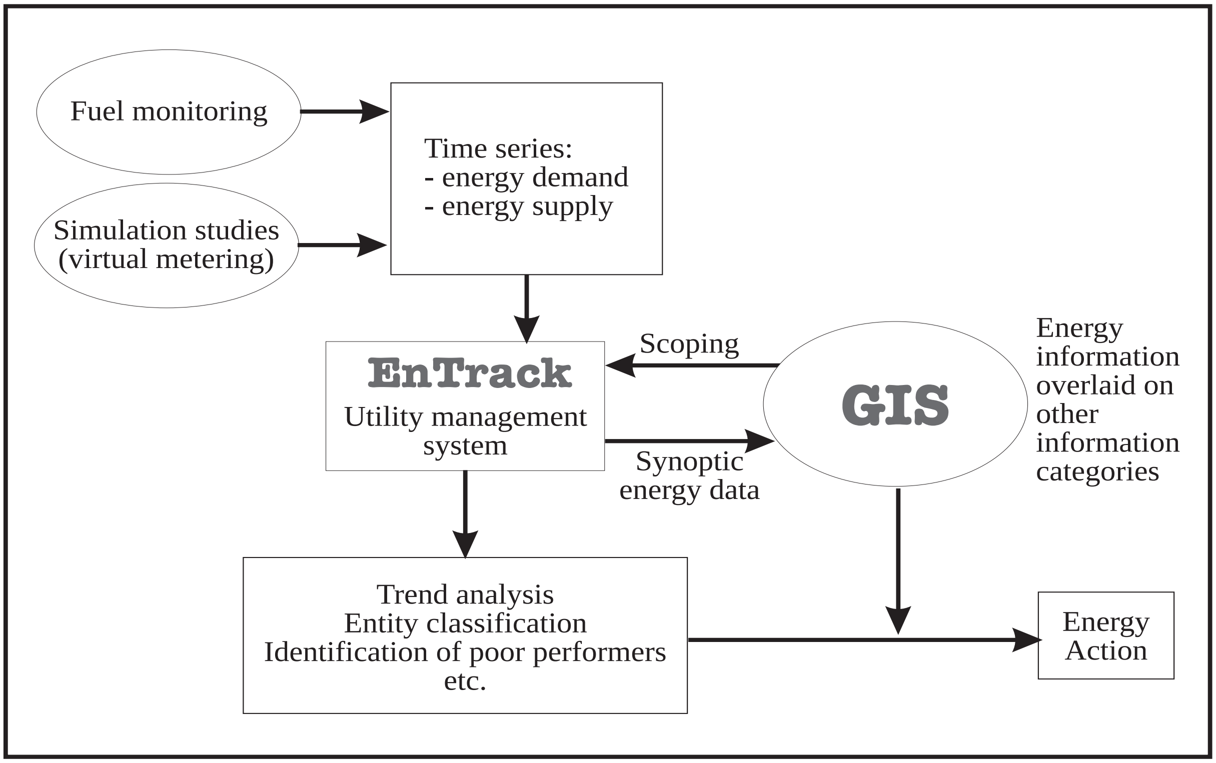

Figure 1: The EnTrack-GIS System.

RE utilisation as opposed to importation via the electric grid.

The EnTrack-GIS system provides the following functionality.

- The quantification of energy demand by fuel type, sector and time.
- The ranking of alternative building energy efficiency measures.
- The assessment of autonomous (e.g. photovoltaic facade) or grid connected (e.g. wind farm) renewable energy schemes from a standpoint of technical feasibility and planning acceptability.
- The imposition of environmental and socio-economic impact considerations.
- The correlation of energy supply with demand, on a spatial and temporal basis, for a single entity or at the institutional/regional scale.

The system is seen as an aid to the regional planning/management process where objective, subjective, social and political considerations must be balanced. It functions as a bridge between this process and the building design activity where specific decisions on autonomous renewable energy integration are taken.

EnTrack-GIS OPERATION

In use, the EnTrack module offers constant monitoring and integration of fuel/power profiles relating to existing properties and renewable energy schemes. The system also offers entity performance classification, trend analysis and targeting, and the assessment of cost effectiveness. For proposed schemes, or where monitored data are unavailable, EnTrack-GIS employs the ESP-r system [4] for building simulation, and the RenSim system [5] for renewable scheme simulation. The output from these simulations can be imported to Entrack's database as virtual meters. By combining real and virtual meter data, with appropriate scaling factors, demand-to-supply matching studies are enabled at the large scale. To support these simulations, EnTrack down-loads scoping information from the GIS, applies its local analysis capabilities, and delivers the outcome back to the GIS. For example:

- For the case of a wind farm feasibility study, parameters such as site exposure/access, community proximity and grid connectability could be down-loaded and, after wind farm simulation, an estimate of the practical wind resource returned for display.

- For the case of a combined heat and power scheme feasibility study, the transaction could entail the down-loading of building design information, and the up-loading (after building simulation) of seasonal heat-to-power ratios.

EnTrack-GIS also offers a procedure for the assessment of the environmental impact of RE developments. This procedure classifies a number of factors on a 3-point scale. These factors are split into two categories: those which affect the technical feasibility of the proposal, and those that are influenced by local or national environmental policy. The categories are summarised in Table 1.

Table 1: Environmental assessment categories.

Category 1	• proximity to point of energy delivery (grid line or local user) • general category of land • access to site
Category 2	• bird populations • landscape value • scientific/ archaeological interest • air traffic/ telecommunications • proximity to dwellings, etc.

The assessment may be made by computing a total "score" for a given proposal or, alternatively, a poor rating in one or more key category might be deemed to make the proposal unacceptable. This allows the GIS to overlay these factors, along with the energy assessments, on the geographical information conventionally stored. The features of EnTrack-GIS include:

- user interaction via sensitised maps and related menus;
- a standard format for data recording and presentation;
- a substantial database of demand- and supply-side statistics;
- a range of analyses, including trend assessment and forecasting;
- renewable energy resource simulation;
- building fuel and power demand simulation;
- matching of demand and supply profiles by time, location and fuel type against imposed constraints;
- and quantification of socio-economic and environmental factors.

It is foreseen that the extent to which EnTrack-GIS can provide comprehensive planning, energy management and specific design support is limited only by the availability of high quality data of adequate resolution - or the ability to generate this by simulation at the time of need. At the present time, EnTrack has knowledge of 7 client data-sets comprising monthly fuel consumption data for approximately 10,000 properties and 3000 renewable energy schemes over multiple year periods.

ROLE OF SIMULATION

On the basis of linear regression techniques applied to historical data, EnTrack is able to generate prediction equations for single entities or entity clusters. Such equations may then be used to estimate performance for anticipated climate conditions. Also, by arranging entities into groups according to energy consumption or production, each with its own characteristic mathematical model, the effect of change may be investigated: e.g. improving the performance of a building, or group of buildings to move it/them from one category to another. Facilities exist to help identify the differentiating design parameters between buildings of similar type but different consumption. For cases where monitored data are unavailable, simulation can be used to generate virtual meter data. EnTrack-GIS employs two simulation tools: ESP-r and RenSim.

The ESP-r System

The ESP-r system [4] was originally established to model a building in terms of the air, moisture and energy flows within and between the elements and components comprising the fabric, items of plant and special systems (such as daylight responsive luminaires). To facilitate the study of RE integration, in terms of issues such as PV-facades, local scale wind power and co-operative switching with the grid, an electrical power flow model has been established in ESP-r as described below.

The building’s electrical system is represented as series of interconnected nodes, where each node represents an electrical bus bar at which conductors (such as distribution cables), loads and generation sources connect. At each node, power is either generated, absorbed by a load or transmitted, with the summation being identically zero. Because equipment impedances are generally unknown, and power consumption data is readily available, loads are treated as complex powers. Similarly, generation is modelled as a source of power (as opposed to a voltage or current source). The purpose of the power flow simulation is to determine the node voltage and phase angles, the real and reactive power flow between nodes and the system transmission losses. The network solution will also reveal the power requirements/surplus for import/export in a grid connected system. If the system is autonomous then the power requirement is that which must be supplied by standby generators.

The required condition for solution of the network is that all loads are known and that models exist to determine the power source output (e.g. for photovoltaic modules and generators). The calculation of these loads/power sources comprises the interface between the ESP-r's thermal and power simulation subsystems, with the former supplying load and generated power information at each time-step. Nodes are connected by power carrying components - such as transmission lines and transformers - which are represented by admittance (the inverse of complex impedance).

Based on the defined network, a power balance calculation is applied at each node and the nodal voltages iteratively adjusted until the power balance residual falls below some acceptable limit. In this way, the power transmitted at any node is evaluated as a function of the voltages at all other nodes in the network. A detailed description of ESP-r's approach to integrated power flow simulation is given elsewhere [5]; what follows is a summary of the approach.

For an arbitrary node i in the network, conservation of power gives

$$S_{gi} = S_{li} + S_{ti} \tag{1}$$

where S_{gi} is the generated power flowing to the node, S_{li} is the load flow from the node and S_{ti} is the transmitted power flowing from the node. In each case, S is a complex vector which can be resolved into real (P) and reactive (Q) components such that $S = P + jQ$, where $P_{gi} = P_{li} + P_{ti}$ and $Q_{gi} = Q_{li} + Q_{ti}$. The analysis is performed on a single phase, assuming phase symmetry, with the result applied to each phase of the n-phase system. For the ith node:

$$S_{ti} = V_i I_i^* \tag{2}$$

where V_i is voltage and I_i^* refers to the conjugate of I_i, i.e. if $I_i = I\angle\phi$ (in polar notation) then $I_i^* = I\angle-\phi$ where ϕ is the current phase angle. Similarly, V can be written as $V\angle\delta$, where δ is the voltage phase angle. The current is therefore given by

$$I_i^* = \sum_{j=1}^{n} V_j Y_{ij}\angle(-\delta_j - \gamma_{ij}). \tag{3}$$

where n is the total number of node couplings, Y_{ij} is related to the admittance of the ij coupling and γ_{ij} is the admittance phase angle, where $Y_{ij}\angle\gamma_{ij} = 1/(R_{ij} + jX_{ij})$. Substituting eqn (3) into eqn (2) gives

$$S_{ti} = \sum_{j=1}^{n} V_i V_j Y_{ij}\angle(\delta_i - \delta_j - \gamma_{ij}). \tag{4}$$

Splitting eqn (4) into real and imaginary parts gives

$$P_{ti} = \sum_{j=1}^{n} V_i V_j Y_{ij}\cos(\delta_i - \delta_j - \gamma_{ij}); \tag{5a}$$

$$Q_{ti} = \sum_{j=1}^{n} V_i V_j Y_{ij}\sin(\delta_i - \delta_j - \gamma_{ij}). \tag{5b}$$

For a network of n nodes, application of eqns (5) gives rise to $2 \times n$ non-linear equations requiring simultaneous solution. This is achieved by an iterative Newton-Raphson technique deployed to solve for the node voltages and phase angles. For node i in an n node scheme, two equations in two unknowns can be formulated as follows.

$$P_i(\delta_i, V_i) = P_{gi} - P_{li} + P_{ti} = 0; \tag{6a}$$

$$Q_i(\delta_i, V_i) = Q_{gi} - Q_{li} + Q_{ti} = 0. \tag{6b}$$

Application of a Taylor series expansion to eqns (6) gives

$$P_i(\delta_i, V_i)_{k+1} = P_i(\delta_i, V_i)_k + \frac{\partial P(\delta_i, V_i)_k}{\partial \delta_i}\Delta\delta_i + \frac{\partial P(\delta_i, V_i)_k}{\partial V_i}\Delta V_i + \cdots$$

$$Q_i(\delta_i, V_i)_{k+1} = Q_i(\delta_i, V_i)_k + \frac{\partial Q(\delta_i, V_i)_k}{\partial \delta_i}\Delta\delta_i + \frac{\partial Q(\delta_i, V_i)_k}{\partial V_i}\Delta V_i + \cdots$$

where k defines the iteration number. Truncating these expressions and simplifying the notation so that $P(\delta_i, V_i)_k = P_{i_k}$, $P_{i_{k+1}} - P_{i_k} = \Delta P_i$, and $V_{i_{k+1}} - V_{i_k} = \Delta V_i$ (with similar simplifications for δ_i and Q_i) gives

$$\Delta P_i = \frac{\partial P_{i_k}}{\partial \delta_i}\Delta\delta_i + \frac{\partial P_{i_k}}{\partial V_i}\Delta V_i; \qquad (7a)$$

$$\Delta Q_i = \frac{\partial Q_{i_k}}{\partial \delta_i}\Delta\delta_i + \frac{\partial Q_{i_k}}{\partial V_i}\Delta V_i. \qquad (7b)$$

Eqns (7) can now be re-written in matrix format:

$$\begin{bmatrix}\Delta P_i \\ \Delta Q_i\end{bmatrix} = \begin{bmatrix}\frac{\partial P_{i_k}}{\partial \delta_i} & \frac{\partial P_{i_k}}{\partial V_i} \\ \frac{\partial Q_{i_k}}{\partial \delta_i} & \frac{\partial Q_{i_k}}{\partial V_i}\end{bmatrix} \times \begin{bmatrix}\Delta\delta_i \\ \Delta V_i\end{bmatrix} \qquad (8)$$

with the matrix of partial derivatives termed the Jacobian matrix, J. Since P_i and Q_i should be identically zero:

$$P_{i_{k+1}} - P_{i_k} = 0 - P_{i_k} \Rightarrow \Delta P_i = -P_{i_k}; \qquad (9a)$$

$$Q_{i_{k+1}} - Q_{i_k} = 0 - Q_{i_k} \Rightarrow \Delta Q_i = -Q_{i_k}. \qquad (9b)$$

Expanding eqn (8) for all n nodes gives

$$\begin{bmatrix}\Delta P_1 \\ \Delta P_2 \\ \vdots \\ \Delta P_n \\ \cdots \\ \Delta Q_1 \\ \Delta Q_2 \\ \vdots \\ \Delta Q_n\end{bmatrix} = \begin{bmatrix}\frac{\partial P_{1_k}}{\partial \delta_1} & \cdots & \frac{\partial P_{1_k}}{\partial \delta_n} & \vdots & \frac{\partial P_{1_k}}{\partial V_1} & \cdots & \frac{\partial P_{1_k}}{\partial V_n} \\ \vdots & & \vdots & \vdots & \vdots & & \vdots \\ \frac{\partial P_{n_k}}{\partial \delta_1} & \cdots & \frac{\partial P_{n_k}}{\partial \delta_n} & \vdots & \frac{\partial P_{n_k}}{\partial V_1} & \cdots & \frac{\partial P_{n_k}}{\partial V_n} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \frac{\partial Q_{1_k}}{\partial \delta_1} & \cdots & \frac{\partial Q_{1_k}}{\partial \delta_n} & \vdots & \frac{\partial Q_{1_k}}{\partial \delta_1} & \cdots & \frac{\partial Q_{1_k}}{\partial V_n} \\ \vdots & & \vdots & \vdots & \vdots & & \vdots \\ \frac{\partial Q_{n_k}}{\partial \delta_1} & \cdots & \frac{\partial Q_{n_k}}{\partial \delta_n} & \vdots & \frac{\partial Q_{n_k}}{\partial \delta_1} & \cdots & \frac{\partial Q_{n_k}}{\partial V_n}\end{bmatrix} \times \begin{bmatrix}\Delta\delta_1 \\ \Delta\delta_2 \\ \vdots \\ \Delta\delta_n \\ \cdots \\ \Delta V_1 \\ \Delta V_2 \\ \vdots \\ \Delta V_n\end{bmatrix}$$

which can be be re-written as

$$\begin{bmatrix}\Delta\tilde{P} \\ \Delta\tilde{Q}\end{bmatrix} = \begin{bmatrix}J_{\left(\frac{\partial P_{n_k}}{\partial \delta_n}\right)} & J_{\left(\frac{\partial P_{n_k}}{\partial V_n}\right)} \\ J_{\left(\frac{\partial Q_{n_k}}{\partial \delta_n}\right)} & J_{\left(\frac{\partial Q_{n_k}}{\partial V_n}\right)}\end{bmatrix} \times \begin{bmatrix}\Delta\tilde{\delta} \\ \Delta\tilde{V}\end{bmatrix} \qquad (10)$$

in which the Jacobian matrix is decomposed into its four constituent parts, and $\Delta\tilde{\delta}$ and $\Delta\tilde{V}$ are given by

$$\Delta\tilde{\delta} = \begin{bmatrix}\Delta\delta_1 \\ \Delta\delta_2 \\ \cdot \\ \cdot \\ \cdot \\ \Delta\delta_n\end{bmatrix} \qquad \Delta\tilde{V} = \begin{bmatrix}\Delta V_1 \\ \Delta V_2 \\ \cdot \\ \cdot \\ \cdot \\ \Delta V_n\end{bmatrix} \qquad (11)$$

with similar column matrix expressions for $\Delta\tilde{P}$ and $\Delta\tilde{Q}$. Rearranging eqn (11) to solve for $\Delta\tilde{\delta}$ and $\Delta\tilde{V}$ gives

$$\begin{bmatrix}\Delta\tilde{\delta} \\ \Delta\tilde{V}\end{bmatrix} = \begin{bmatrix}J_{\left(\frac{\partial P_{n_k}}{\partial \delta_n}\right)} & J_{\left(\frac{\partial P_{n_k}}{\partial V_n}\right)} \\ J_{\left(\frac{\partial Q_{n_k}}{\partial \delta_n}\right)} & J_{\left(\frac{\partial Q_{n_k}}{\partial V_n}\right)}\end{bmatrix}^{-1} \times \begin{bmatrix}\Delta\tilde{P} \\ \Delta\tilde{Q}\end{bmatrix} \qquad (12)$$

Hence, new estimates for V and δ for each node can be found from

$$\tilde{\delta}_{k+1} = \tilde{\delta}_k + \Delta\tilde{\delta}; \qquad (13a)$$

$$\tilde{V}_{k+1} = \tilde{V}_k + \Delta\tilde{V} \qquad (13b)$$

with the iteration process ending when $|\tilde{V}_{k+1} - \tilde{V}_k|$ and $|\tilde{\delta}_{k+1} - \tilde{\delta}_k|$ reach a pre-defined limit. Relaxation factors are included to handle the case of slow or oscillatory convergence

This solution method can also be applied to DC systems. In this case, Q is zero, Y becomes conductance, V is a scalar quantity and the number of equations falls from $2n$ to n. The Jacobian matrix then consists of only the dP/dV terms so that $\Delta\tilde{V} = \left[\frac{\delta P}{\delta V}\right]^{-1} * \Delta\tilde{P}$.

Within ESP-r, a power flow simulation may be initiated independently of the integrated solver or in tandem. In the latter case, loads in the network may be actuated as a function of time, indoor daylight illuminance, small power usage, occupant scheduling, etc., with power supplied from active models representing photovoltaic modules, batteries, diesel generators and the electric grid. Use of such an integrated approach allows explicit simulations of combined heat and power and hybrid RE/grid schemes. Further details on the power flow modelling approach, and its implementation within the ESP-r system, are given elsewhere [6].

The RenSim System

The capacity exists within EnTrack-GIS to record production data from renewable energy conversion systems of any kind. Such systems are, of course, still few in number. To investigate future scenarios, in which RE development is more intensive, two approaches are possible:

- Where a system already exists, which may be regarded as prototypical, it may be "duplicated" in a new location.
- The output of hypothetical systems may be modelled as a function of climate and other variables, using simulation techniques. The RenSim system has been incorporated within EnTrack-GIS for this purpose.

On the basis of information supplied by EnTrack-GIS (describing a proposed renewable energy installation and location-specific climate), RenSim is able to assess the time-dependent resource and transfer this to EnTrack's database for analysis alongside the other demand- and supply-side entities therein. Where a renewable energy resource assessment is required for an area or region, this may be achieved by replicating these data at an appropriate density, subject to environmental, economic and other constraints. The ability to access temporal distributions, and later to correlate them with corresponding distributions of demand, is seen as a major advance on current methodologies.

At the present time, RenSim has installed models for most renewable energy sources including wind, hydro, forestry and agricultural wastes, municipal wastes, energy crops, wave (onshore and near offshore) and geothermal. The models vary greatly in their nature and complexity. As an example, consider the model for wind power assessment.

In simplest terms, the performance of a wind turbine may be characterised by the way in which its power coefficient C_p varies with tip speed ratio λ. The power output is given by

$$P = C_p \, \tfrac{1}{2} \, \rho V_\infty^3 \pi R_T^2 \qquad (14)$$

where ρ is the air density, V_∞ is the wind speed and R_T is the rotor radius. The tip speed ratio is defined by

$$\lambda = \Omega \frac{R_T}{V_\infty} \qquad (15)$$

where Ω is the angular velocity of the rotor. Provided that V_∞, Ω and the relationship between C_p and λ are known, the output from the turbine may be calculated. A complication arises if variable-pitch blading is fitted; C_p then depends upon λ and the blade pitch angle. If the characteristics of the turbine are not fully known, they may be predicted with reasonable accuracy from blade element theory [7]. The flow through the rotor is divided into a number of annular elements; for each, the local wind velocity at the rotor plane is defined as $V_\infty(1-a)$, a being unknown. For a blade element at radius r, a momentum balance is drawn up between the force exerted by the rotor on the air stream:

$$dF = 4\pi r \rho V_\infty^2 a(1-a) dr \qquad (16)$$

and the reaction force on the rotor, in terms of aerofoil lift and drag coefficients C_L and C_D,

$$dF = \tfrac{1}{2} \rho WBC[C_L \Omega r(1+a') + C_D V_\infty (1-a)] dr \qquad (17)$$

where $W^2 = V_\infty^2 (1-a)^2 + \Omega^2 r^2 (1+a')^2$, B is the number of blades and C is the blade chord at radius r.

Likewise, in the tangential direction a momentum balance is established: the wake behind the rotor is assumed to be rotating with angular velocity ω, from which a tangential velocity parameter a' is defined:

$$a' = \frac{\Omega}{2\omega} . \qquad (18)$$

The torque exerted on the wake by the blading is then given by

$$dT = 4\pi r^3 \rho V_\infty (1-a) a' \Omega dr \qquad (19)$$

and the reaction torque on the rotor by

$$dT = \tfrac{1}{2} \rho WBC[C_L V_\infty (1-a) - C_D \Omega r(1+a')] r dr . \qquad (20)$$

The equations for axial and tangential momentum are solved iteratively for a and a', for each element of the rotor area in turn, after which the entire flow field is established and the power output from the turbine calculated. For variable-speed or variable-geometry machines, repeated application of the method will predict the full range of characteristics.

Proposals have been made for building-integrated wind turbines, using ducted rotors of unconventional design [8]; at present they seem to

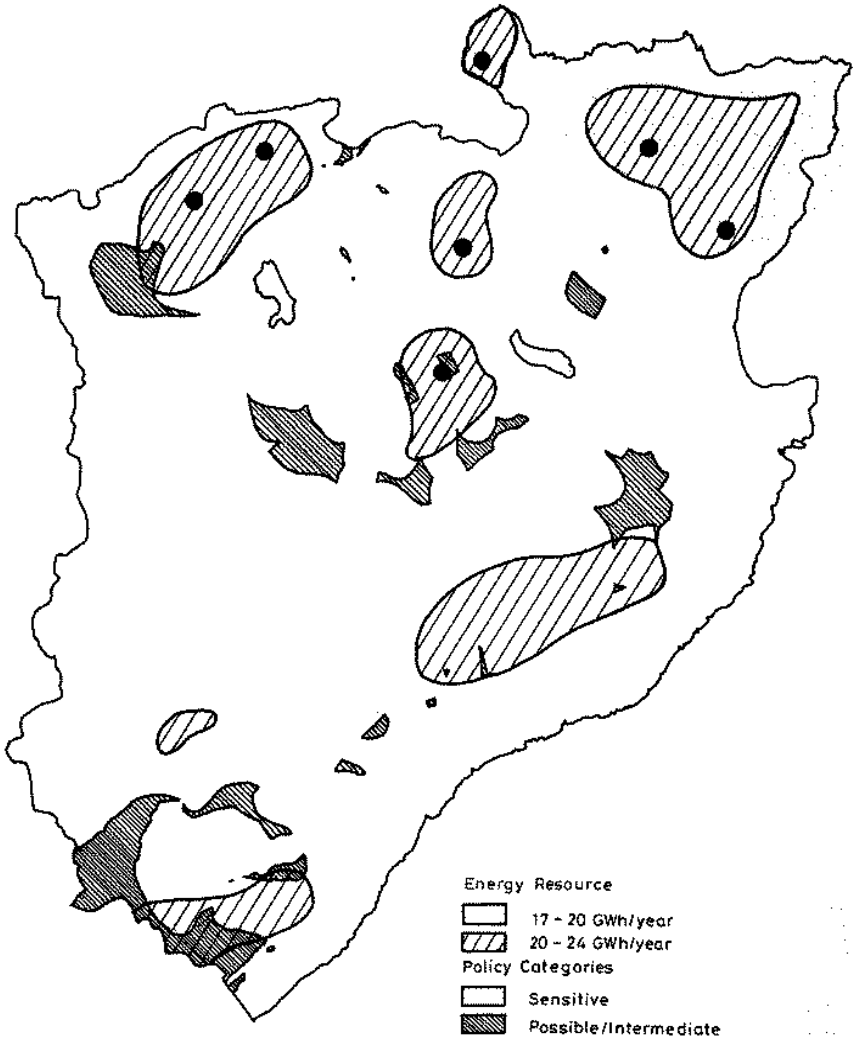

Figure 2: Resource/opportunity map, wind farms, Caithness.

be a long way from commercial exploitation. Rigorous analysis of such devices is complex, and characteristics would be based upon empirical relationships between power output and controlling parameters such as rotor speed, wind speed and direction. However, for the autonomous use of conventional wind turbines, simulation for use in EnTrack-GIS would proceed as above.

EnTrack-GIS FIELD TRIALS

To establish the EnTrack-GIS system's applicability, a field trial has been conducted in relation to the formulation of an energy action plan for wind power in the district of Caithness in the Scottish Highlands.

An initial resource assessment was conducted (on the basis of the model previously derived and scoping data down-loaded from the GIS) against two sets of criteria: technical (Category 1 in Table 1) and environmental (Category 2). It became clear that Caithness has an excellent wind energy resource, but when particularly environmental considerations are applied, the acceptable locations are limited. This is clear from Figure 2 which shows, on a GIS-generated map, the predicted areas for development of wind farms under the stringent criteria presently applied by the regional authority. A number of specific proposals for development in Caithness have already been made, and their locations are shown in Figure 2. Table 2 gives the outcome of a technical and environmental assessment of these proposals using the criteria listed in Table 1 to compile a numerical rating: a low number is desirable in each category. It will be noted that only one falls within an area of opportunity on the map.

Table 2: Wind farms, overall ratings.

Site	Technical (Scale 3 -> 8)	Environ. (Scale 8 -> 20)	Rank Order
Hill of Forss	3	13	4=
Bardnaheigh	3	13	4=
Spittal Hill	3	11	1
Slickly	5	11	3
Durran Mains	3	14	6
Hill of Clayton	5	13	5
Dunnet Hill	4	11	2

It is clear that unless the criteria are relaxed, the prospects for wind farms in the area are bleak. A possible alternative, is the autonomous or local use of small clusters or single wind turbines, for which planning restrictions are likely to be less severe. EnTrack-GIS was used to investigate the correlation between wind energy supply and local demand. As is generally the case in Scotland, there was a strong positive seasonal correlation, the main shortfalls occurring in the summer months. It was concluded that there were significant opportunities in this type of approach.

A local network was then simulated according to the schematic shown in Figure 3, using short timescales to predict electrical import/export time series for the local grid. The ultimate refinement is to conduct detailed power integration studies by establishing specific building/wind turbine models, and undertaking ESP-r power flow simulations. The schematic of Figure 3 remains valid, with individual loads replacing local users. Energy storage (hot water, lead-acid batteries, etc.) is included to alleviate short-term mismatches between supply and demand. "Virtual metering" will generate information on running costs to input to an overall economic analysis.

Alternative utilisation scenarios may thus be investigated in terms of their effects on imports/exports to the local electrical grid, the consumption of other fuels, system power factors and reliability and the impact on the local economy/environment. Such information is the prerequisite of local energy action plans.

CONCLUSIONS

The issues surrounding renewable energy utilisation are complex and areas of uncertainty abound. As a response to this situation, a decision support system has been developed for use by planners, energy managers and designers. Protocols have been devised for communication between the EnTrack fuel monitoring system and a GIS system. EnTrack-GIS has been configured with substantial databases of energy demand and renewable energy supply. Simulators for renewable energy conversion and power processing systems have been developed to permit an assessment of the impact of hypothetical schemes.

The EnTrack-GIS system may be used to generate information on the most favoured location for a renewable energy development, or to carry out energy supply/demand matching exercises at a local or regional scale. A large amount of data may be assembled and processed, and many different policy scenarios can be examined. A framework for the assessment of environmental, social and economic impacts has been incorporated, to allow comparisons to be made.

The outcomes from such assessments may be presented in a variety of ways: maps where issues such as access or competition for land are important; graphs, where seasonal variations in energy supply or demand are of concern; or in tabular form, to give either qualitative or numerical assessments. When compared with current practices in regional development and planning departments, it is clear that there is the potential for great savings in time and effort.

Finally, a cautionary note. The information produced can never be regarded as exhaustive, and cannot fully cover the less quantifiable issues, which can only be resolved by wider consultation. Therefore, while the EnTrack-GIS system has been shown to be a powerful strategic information processing tool, it cannot be applied rigidly. This is symptomatic of the fact that the planning process is multi-disciplinary in nature, involving subjective social and political considerations, as well as the more objective issues covered here.

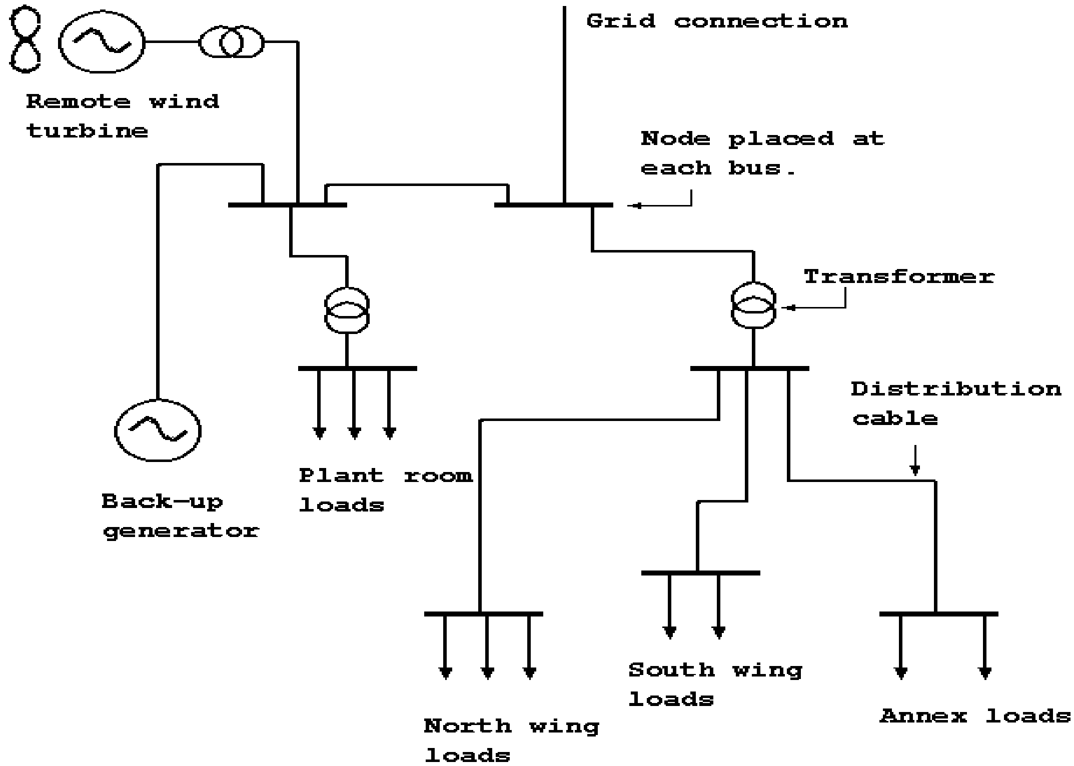

Figure 3: An ESP-r power flow network.

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