The Resource Development Plan

13

This chapter sets the likely scene at the conception of a geothermal power project and then discusses how the power station capacity can be estimated using an elementary method. Numerical reservoir simulation is introduced as a planning and prediction tool, and its mathematical basis is outlined before returning to the identification of the main stages of a project and typical environmental impacts.

13.1 The First Stages of Planning

At the start of a development, all that will be known is that a geothermal resource exists beneath the land area available, that there is a demand for electricity and that transmitting it will be possible. The legislation governing geothermal resource use will have been identified. By the time the plan is complete enough to present to the authorities with the responsibility for making a decision, the power station site, transmission line corridors, land area on which wells are to be drilled and approximate pipeline routes will have been defined. The final prime movers are often still undefined at this stage, but all the major surface equipment needed will be known sufficiently for their environmental impact to be assessed. Enough wells will have been drilled, under an exploration permit, to convince the developer’s bank to fund the enterprise, but the project will not be commercially risk free; the permitting authority will understand this, but so long as the development is in the national interest and the environmental impact is acceptable, then permits may be granted. This is the case in New Zealand (where permits are referred to as resource consents) and is probably a likely scenario anywhere.

The procedure would be the same if a fossil-fuelled plant was to be built, and the next step would be to design it, working from major parameters first to final manufacturing detail. The way the equipment functions is known in detail—every component is designed for a specific purpose, and its performance is known from engineering calculations and laboratory tests. In contrast, a natural geothermal resource is unique in every detail—it may be the result of recognisable physical processes, but how the fluids circulate and the response to drilling, production and

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injection have to be explored and measured. Some risk that the resource will not supply heat and fluid at the estimated rate must be accepted. Extreme caution is unhelpful as the economic advantage of a particular geothermal plant over a fossil-fuelled alternative might be slim, but not enough caution will result in idle plant which has to be sold at a loss.

The chronological steps in formulating a plan are typically as follows:

(a) Explore the surface geology and conduct geophysical studies to help estimate geological stratigraphy and structure and determine possible boundaries of the system.

(b) Conduct geochemical investigation of surface discharges to help determine its hydrology and temperature distribution; this will include planning the sites and numbers of wells needed to give sufficient information and will involve scientists and engineers. Well sites positioned for easy use later will be preferred.

(c) Knowing the surrounding area and its uses, plan a strategy for extracting the hot resource fluid and injecting it at lower temperature, including possible schemes for how to respond to future reductions in energy output from the wells. This is the task for which numerical reservoir simulation was primarily developed, but it is also useful for step (b).

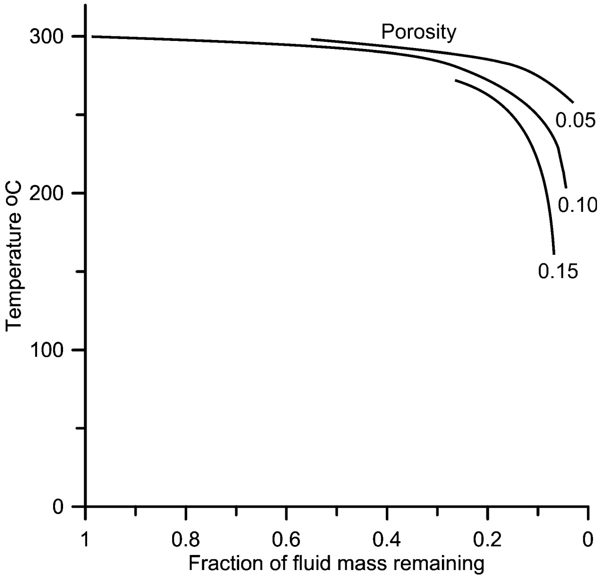
(d) Decide on the power station capacity and type. Reservoir simulators now play a part in this step, but a simpler methodology was developed earlier, called a stored heat estimate.

13.2 A Stored Heat Estimate

Resource assessment in general attempts to answer the question "what installed generating capacity can the resource supply for at least the term of the loan taken out to fund the project?". The question may be asked before many wells have been drilled and tested. A stored heat estimate was the usual way of providing an answer until the 1980s and remains a worthwhile exercise.

The UK consulting company Merz and McLellan [1956], under contract to the NZ government in relation to the development of Wairakei, reported at one stage on the generating capacity that might be installed over and above the 69 MWe that had already been committed to. It was noted that drilling success had fluctuated since 1953 and that initially deep drilling had been successful but then had fallen behind shallow drilling in terms of output per well, before finally returning to being more successful. Enough steam to support 150 MWe was available at wellhead at the time. A high drilling success rate, it was said, must not be expected to continue indefinitely. A capacity of 250–500 MWe had previously been suggested by the NZ Department of Scientific and Industrial Research, and Merz and McLellan advised the lower of this range as the maximum and that 20 % of capacity should be kept available as steam at wellhead, i.e. stand-by wells ready to produce. Their report is cautiously worded but without any methodology at all and contains no discussion on possible resource decline—the resource is still producing 150 MWe with 95 %

Fig. 13.1 Showing the decline in steam conditions as mass is withdrawn from a resource considered as a single tank of saturated water (*Watson and Maunder* [1982])



availability 60 years later, so the estimate might be said to have been valid, but the fact remains, they produced a resource capacity recommendation without any methodology.

The central problem of resource assessment is that hot water, steam or both are to be extracted from a body of fractured hot rock at a rate very much higher than the rate of replenishment. When viewed as a whole, the mass of fluid contained declines by 2/3 before any significant loss of steam temperature is evident, suggesting that well outputs can decline with little warning after a long period of slow steady decline. This was demonstrated by Whiting and Ramey [1969] using the heat and mass balance equations for the whole resource, an exercise repeated by Watson and Maunder [1982] and shown here as Fig. 13.1.

The stored heat estimate was described by Muffler and Cataldi [1978]. The area of the resource was defined in terms of its resistivity boundary, and its thickness was taken as the distance between the depth at which the rock temperature was 180 °C and 500 m beneath the drilled depth; 180 °C was taken as the minimum useful temperature. A certain proportion of the heat stored in this body of rock was assumed to be recoverable, and a percentage conversion of recovered heat to electricity was stipulated. The stored heat method was used by several organisations, as reviewed by Watson and Maunder [1982], who noted that the minimum temperature adopted varied between 180 and 200 °C, that recovery factors varied from 25 to 100 % and that conversion percentages ranged from 7.5 to 10 %.

A typical calculation is as follows. The fully heated temperature distribution of a well is assumed to characterise the formation temperature in the vicinity. Figure 13.2 is a simple example in which the temperature distribution is

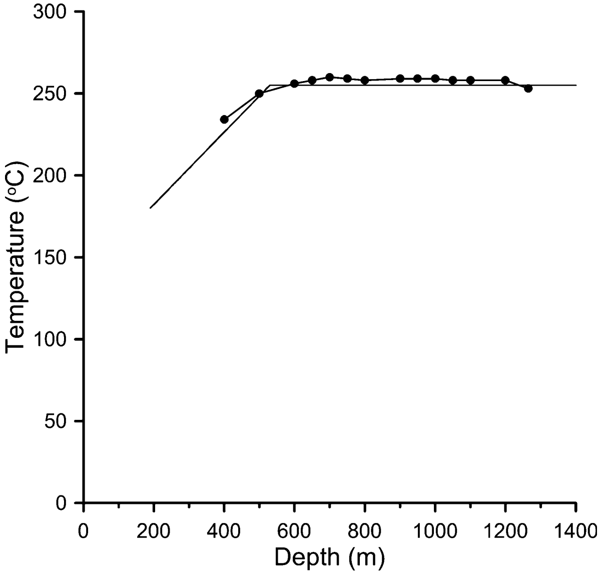


Fig. 13.2 A measured well temperature distribution approximated as two linear portions for a stored heat calculation

approximated as constant at 255 °C from 540 to 1,800 m (500 m below the well depth of 1,300 m) and with a linear variation from 180 °C at 200 m to 255 °C at 540 m, to which an equation can be fitted:

$$T = 0.2206z + 135.9 \tag{13.1}$$

where z is the depth below the surface (m).

Although the resource is usable from a depth of 200 m if temperature is the criterion, assume that the minimum practical depth from which to produce is 400 m. The resource can be considered as two slabs; the lower one from 540 m downwards with a uniform temperature of 255 °C, and the other from 400 to 540 m which, based on Eq. (13.1), has an average temperature $\overline{T}$ of 239.6 °C.

Each cubic metre of resource rock of porosity ϕ has stored heat components due to the rock and to the water in the pores, and for rock of average temperature $\overline{T}$, the total stored heat above 180 °C is Q kJ/m^3 where

$$Q = \left((1-\phi)\rho_R Cp_R + \phi\rho_f Cp_f\right)\left(\overline{T} - 180\right) \tag{13.2}$$

$$= \left(1 + \frac{\rho_f Cp_f \phi}{\rho_R Cp_R (1-\phi)}\right)\rho_R Cp_R (1-\phi)\left(\overline{T} - 180\right) \tag{13.3}$$

$$= \Lambda \rho_R Cp_R \left(\overline{T} - 180\right)\left(\text{kJ/m}^3\right) \tag{13.4}$$

The (dimensionless) group Λ has been gathered because if it is assumed to be unity, then the stored heat can be calculated using the rock properties only.

Table 13.1 Showing the variation of factor Λ with pressure and porosity

Pressure (bar abs)	ϕ	0.05	0.10	0.15
100		1.037	1.074	1.111
150		1.035	1.070	1.105
200		1.034	1.067	1.100

The variation of Λ over a range of porosity and water pressure is shown in Table 13.1, using typical rock properties.

The value of Λ lies between 1.0 and 1.1, and assuming it to be 1.0 represents a small uncertainty compared to that of the recovery factor, which is a pure guess, and the utilisation factor. In other words, the stored heat in the resource can be assumed to be the heat in the rock.

Returning to the example of Fig. 13.2 and assuming $\phi = 0.05$, $\rho_R = 2{,}600\ \text{kg/m}^3$, $Cp_R = 0.9$ kJ/kgK and $\Lambda = 1.0$, then using Eq. (13.4) the heat stored in a column of the resource with a surface area of 1 km^2 is

$$2,600 \times 0.9 \times 1.0\text{E}6[(239.6 - 180) \times (540 - 400) + (255 - 180) \times (1,800 - 540)]$$
$$\text{or} \quad 240.6\text{E}12\ \ \text{J/km}^2$$

If it is assumed that 50 % of this heat is recovered and 10 % is converted to electricity, then the total energy in the form of electricity is 12.03E12 J/km^2. Assuming the energy is extracted steadily over 25 years, then for every square kilometre of the resource, which has the temperature distribution shown in Fig. 13.2, the electrical generation rate will be

$$12.03 \times 10^{12}/(25 \times 8,760 \times 3,600)\ \text{We/km}^2 = 15.3\ \text{MWe/km}^2$$

Circles of area 1 km^2 can be drawn around each well drilled and a capacity figure found for each one based on the heat-up temperature distributions. Wells with a downflow complicate the calculation by obscuring the formation temperature.

The stored heat calculation is very simplistic, but it is so easy to carry out that there can be no reason not to do it, even today. The conclusions presented by Watson and Maunder [1982] are still relevant 30 years after they were written, with the exception that lumped parameter models have been superseded by numerical simulation. They were written while the authors were grappling with the task in reality and they wrote

> "*Arriving at a decision*
> *When the decision point is reached the developer will find himself in possession of several weakly connected sets of information. A stored heat calculation will have been done because it is relatively cost free. Simulation may have been carried out, and may have produced a prediction of field output decline which can be combined with known plant performance to give electrical output over the plant life. Both of these assessments will have incorporated unverifiable assumptions. Unrelated to these are well power output measurements, which give no direct indication of gross power output of the field but*

> *serve to show how many wells will be needed to power a given plant. (Installation of a small turbine, say 1.5 to 3 MWe may give enough information over say 2 years to allow a lumped parameter model to be constructed). The only way to connect these sets of data is* via *an economic analysis of the project. At its basic level this should be a sensitivity study based on various plausible patterns of field behaviour—how frequently new wells will be required, workovers, turbine outage, reinjection problems, etc. At the same time as bringing all the information together, an analysis of this type decreases the importance of assumptions made in modeling or stored heat assessment. It is not sufficient to attempt to apply conservative scientific and engineering assumptions to the reservoir assessment. The uncertainty in reservoir capacity must be translated and quantified as a financial risk*".

Recently, Sanyal et al. [2011] presented what amounted to a risk assessment of geothermal resource development in Indonesia, where enough wells have been drilled to provide a reasonable statistical sample. Their paper related to a plan by the Indonesian government to expand geothermal electricity generation in the country and examined 215 wells which had been drilled at 100 resource sites. It concluded that there was sufficient experience available in assessing and drilling Indonesian resources that the overall resource risk "should be" lower than in other countries—the qualification in parenthesis is a necessary part of reporting on resource and risk assessment.

13.3 Numerical Reservoir Simulation

To simulate a geothermal resource is to describe it by a set of equations written with space and time as independent variables and pressure and temperature as dependent ones and solve them for appropriate boundary conditions. The general process is used in many fields of engineering and consists of writing the governing equations in finite difference form and solving them numerically. Computers able to carry out very fast numerical procedures became available to researchers around 1960; numerical solution procedures for sets of partial differential equations had been developed earlier and had to be carried out by hand, although at least one mechanical analogue computer was developed in the 1930s for aerodynamic design by Hartree. Numerical simulators were developed for petroleum reservoirs towards the end of the 1970s. For petroleum, groundwater and geothermal reservoir simulation, the equations are those describing the flow of fluids through permeable (porous) media, incorporating Darcy's law. As with numerical simulators in other engineering fields, the whole programme is so large and complex that the set of governing equations is invisible to the user, who is presented with an interface allowing the data prescribing the problem to be written as an input file to the main computer programme. An initial pressure and temperature distribution are provided, and changes to it in response to well discharge and injection are calculated, advancing in time. The spatial distribution of variables is available for inspection at times after the start of the calculation requested by the user. The calculation proceeds automatically in time steps that are adjusted to ensure accuracy in the solutions. Although the use of a reservoir simulator as a planning tool is the focus here because it is the only available method of predicting how a resource will respond to the extraction and injection of fluid, they can also be used to examine detailed processes, for example, as part of the transient pressure well testing described in Chap. 9—see, for example, O'Sullivan [1987], who modelled the two-phase flow in the formation and determined formation properties by interpreting changes in flowing enthalpy.

In 1979, the US Department of Energy arranged for the principal research groups internationally to define six problems involving single- and two-phase flow in geothermal resources and then invited the groups to take part in a "competition" to see which simulator was best. Molloy and Sorey [1981] describe the process and the results, which showed that several different reliable simulators were available at that time, in other words, that the general validity of the invisible processing was established for some programmes. An historical perspective of simulators and their predecessors, lumped parameter models, is provided by O'Sullivan et al. [2009] in describing the numerical modelling of Wairakei.

To fulfil the aims of this book, it is necessary to examine the way the simulator functions. There are several textbooks on petroleum reservoir simulation, e.g. Critchlow [1977], which give details of the numerical procedures, but having been developed and proven over 30 years, most of the literature on the subject deals with applications. Given in the next section is a basic introduction. Gelegenis et al. [1989] provide a detailed insight into the calculation procedure used in their own geothermal reservoir simulator, and their paper might form the next level of study. The TOUGH2 simulator is probably the most often used today, and the various manuals related, e.g. Pruess [1987], give user information that includes some calculation details.

13.3.1 The Mathematical Basis of a Geothermal Reservoir Simulator

The governing equations are a partial differential set which must be changed into a numerical set, or "discretised", and then solved simultaneously. The process can be illustrated by examining the solution of Eq. (13.5), which describes the thermal conduction taking place in a long metal bar, thermally insulated and initially at uniform temperature, when a heat source is applied to one end at time $t = 0$. The temperature distribution along the bar at any time is to be found. A more general form of this equation was given as Eq. (4.65), which without the heat source term and reduced to one dimension becomes

$$\frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial x^2} \tag{13.5}$$

The formal method of converting this equation into numerical form is to write a Taylor series expansion of T and its gradients with x:

$$T' = \frac{\partial T}{\partial x}, T'' = \frac{\partial^2 T}{\partial x^2}, T''' = \frac{\partial^3 T}{\partial x^3}, etc$$

as

$$T(x+\Delta x) = T(x) + \Delta x.T'(x) + \frac{1}{2}\left(\Delta x^2\right)T''(x) + \frac{1}{6}\left(\Delta x^3\right)T'''(x)\cdots \tag{13.6}$$

$$T(x-\Delta x) = T(x) - \Delta x.T'(x) + \frac{1}{2}\left(\Delta x^2\right)T''(x) - \frac{1}{6}\left(\Delta x^3\right)T'''(x)\cdots \tag{13.7}$$

Neglecting all terms containing Δx^3 and higher powers, the remaining terms of these two equations can be eliminated or rearranged to obtain three expressions for the temperature gradient T′ and one for the second derivative T″, and these are named as shown:

$$T' = \frac{(T(x+\Delta x) - T(x))}{\Delta x} \quad \text{forward difference} \tag{13.8}$$

$$T' = \frac{(T(x) - T(x-\Delta x))}{\Delta x} \quad \text{backward difference} \tag{13.9}$$

$$T' = \frac{(T(x+\Delta x) - T(x-\Delta x))}{\Delta x} \quad \text{central difference} \tag{13.10}$$

$$T'' = \frac{(T(x+\Delta x) + T(x-\Delta x) - 2T(x))}{\Delta x^2} \tag{13.11}$$

The same approach can be adopted for gradients of T with time. Equation (13.11) can now be substituted into the right-hand side of Eq. (13.5), but there is a choice of expressions for the first derivative of temperature with time, analogous to Eqs. (13.8) and (13.9). How the temperature develops with time is to be found, so a forward difference form is the intuitive choice, for which the discretised form of Eq. (13.5) is

$$\frac{T_i^{n+1} - T_i^n}{\Delta t} = \kappa\frac{\left(T_{i+1}^n + T_{i-1}^n - 2T_i^n\right)}{\Delta x^2} \tag{13.12}$$

where T_i^n is the temperature at location i at time n. The locations are referred to as nodes, the distance between nodes is Δx and the time step from n to n + 1 is Δt. Figure 13.3 shows how the solution advances in time.

The rationale for choosing the values of Δx and Δt is based on a reorganisation of Eq. (13.12) into the form

$$\begin{aligned} T_i^{n+1} &= \left(\frac{\kappa\Delta t}{\Delta x^2}\right)\left(T_{i+1}^n + T_{i-1}^n - 2T_i^n\right) + T_i^n \\ &= F\left(T_{i+1}^n + T_{i-1}^n + \left(\frac{1}{F} - 2\right)T_i^n\right) \end{aligned} \tag{13.13}$$

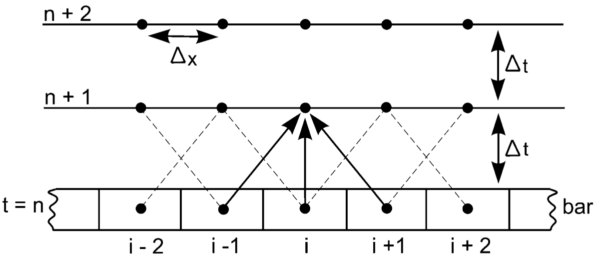


Fig. 13.3 Showing the influence of nodal values in a finite difference solution for one-dimensional transient thermal conduction

The equation has been rearranged in this way because F is the Fourier number of Eq. (4.67), written here as

$$F = \frac{\kappa \Delta t}{\Delta x^2} \tag{13.14}$$

Equation (13.13) shows that if F = 1/2, the influence of the temperature at node i is lost, which is clearly unreasonable—see Fig. 13.3—so the solution only works with F less than this. A choice of Δx then leads to Δt or vice versa. Boundary conditions can be applied, either a fixed temperature at a node or a fixed gradient by means of an "artificial" node at the end of the bar. This method can be set up using a spreadsheet (an instructive learning exercise) because it is explicit, that is, the values at the next nodes in time depend only on known information and not on the neighbouring values at the new time. The values at the new times are calculated individually.

It is physically unreasonable to expect that the value T_i^{n+1} will not be affected by T_{i-1}^{n+1} and T_{i+1}^{n+1}, and correcting this makes the solution implicit, that is, the values for every node at the new time step must be solved simultaneously because they depend on each other. Equation (13.5) can be written in terms of the unknown node values at the new time step, with the influence of the previous time step still present through the nearest neighbour, T_i^n:

$$\frac{T_i^{n+1} - T_i^n}{\Delta t} = \kappa \frac{\left(T_{i+1}^{n+1} + T_{i-1}^{n+1} - 2T_i^{n+1}\right)}{\Delta x^2} \tag{13.15}$$

and this equation can be generalised as

$$a_{i-1} T_{i-1}^{n+1} + b_i T_i^{n+1} + c_{i+1} T_{i+1}^{n+1} = d_i \tag{13.16}$$

in which a, b, c and d are known coefficients for every node, incorporating the previous values of T and the Fourier number. A set of equations of this type, centred around each node, can be written as

$$\begin{array}{lllllllll}
a_{i-1}T_{i-2}^{n+1} & + & b_{i-1}T_{i-1}^{n+1} & + & c_{i-1}T_{i}^{n+1} & & & = & d_{i-1} \\
 & & a_{i}T_{i-1}^{n+1} & + & b_{i}T_{i}^{n+1} & + & c_{i}T_{i+1}^{n+1} & = & d_{i} \\
 & & & & a_{i+1}T_{i}^{n+1} & + & b_{i+1}T_{i+1}^{n+1} \; + \; c_{i+1}T_{i+2}^{n+1} & = & d_{i+1} \\
 & & & & & & \cdots & = & d_{i+2}
\end{array} \tag{13.17}$$

etc.

Computational techniques have been developed for solving sets of equations like this, which form tri-diagonal matrices, and also for sets which are not quite so regular, like the equations describing flow in the resource.

This introduction has dealt with the solution of only one equation, the energy equation, because it is for a solid material, but for flow in permeable materials, two equations are to be solved, one representing continuity of mass and momentum combined by the incorporation of Darcy's law, like Eq. (4.78), and the other the energy equation, and they need to be written for a permeable material and two-phase fluid. To illustrate the equations and express them in terms found in the literature on simulation, Eq. (4.77) is a suitable starting point, an equation expressing mass conservation:

$$\phi\frac{\partial\rho}{\partial t}+\left(\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}\right)=0 \tag{13.18}$$

The first term represents the mass of fluid per unit volume contained in the control volume and the second the net flux (mass flow rate) in each of the three directions. The control volume can be considered as a block. To include the possibility of production or injection, a sink or source term must be included, and the equation is usually written:

$$\frac{\partial A_m}{\partial t}+\nabla F_m+\dot{q}_m=0 \tag{13.19}$$

where

$A_m = \phi(S_v\rho_v + S_l\rho_l)$ is the mass of fluid per unit volume in the block;

S_v and S_l are the saturations (volume fractions) of vapour and liquid, respectively;

∇ is the operator $\frac{\partial}{\partial x}+\frac{\partial}{\partial y}+\frac{\partial}{\partial z}$

F_m is the mass flux (flow rate per unit area) crossing the boundaries of the block then $\dot{q}_m$ is the rate of production of the mass source.

Darcy's law is next introduced to couple momentum and continuity of mass equations. The gravitational term in the momentum equation has been neglected as the main application so far has been to horizontal formations of moderate thickness, but when considering the whole resource, it must be included, and it might as well be included in the equation set for every direction, for regularity, since numerical solutions and not analytical ones are being applied and g set to zero in two of the three directions. Hence the mass fluxes can be written for vapour and liquid phases:

$$F_{mg} = -\rho_g k \frac{k_{rg}}{\mu_g}\left(\nabla P - \rho_g g\right) \tag{13.20}$$

$$F_{mf} = -\rho_f k \frac{k_{rf}}{\mu_f}\left(\nabla P - \rho_f g\right) \tag{13.21}$$

The energy equation can be similarly treated, using the specific internal energy version similar to Eq. (4.23), but adopting the format of Eq. (13.19). However the energy in the rock must be included:

$$\frac{\partial A_e}{\partial t} + \nabla F_e + \dot{q}_e = 0 \tag{13.22}$$

where

$$A_e = (1 - \phi)\rho_r U_r + \phi\left(S_g \rho_g U_g + S_f \rho_f U_f\right) \tag{13.23}$$

and

$$F_e = -\rho_g h_g \frac{k k_{rg}}{\mu_g}\left(\nabla P - \rho_g g\right) - \rho_f h_f \frac{k k_{rf}}{\mu_f}\left(\nabla P - \rho_f g\right) - \kappa \nabla T \tag{13.24}$$

Equations (13.19) and (13.22) must now be discretised, a pair for every block (node) of the resource model, and because they are implicit in the variables to be determined, and non-linear, with coefficients that are functions of P and T, they must be solved iteratively. For this reason, they are written with residuals for every node and time step. Thus for node i at time step $n + 1$,

$$\left[\frac{\partial A_m}{\partial t} + \nabla F_m + \dot{q}_m\right]_i^{n+1} = [R_m]_i^{n+1} \tag{13.25}$$

$$\left[\frac{\partial A_e}{\partial t} + \nabla F_e + \dot{q}_e\right]_i^{n+1} = [R]_i^{n+1} \tag{13.26}$$

By adjusting the time step, the residuals can be minimised until they reach acceptably small values.

The inclusion of a gas dissolved in the reservoir fluid calls for a third equation, and CO_2 was added by Zyvoloski and O'Sullivan [1980], increasing the numerical complexity significantly.

The explanation so far has assumed a regular pattern of nodes throughout the region of interest. A large-volume resource divided at the close spacing required for those parts of the resource where the flow is most complex would result in an excessive number of equations to be solved. A numerical form capable of dealing with whatever irregular node distribution was chosen was introduced by Narasimhan and Witherspoon [1976], called the integrated finite difference method. It was particularly convenient for a system of embedded blocks matching the concept of a dual porosity system as described in Sect. 9.4.3 (see Pruess [1990]). Pruess [1991] explains that the TOUGH2 simulator, which uses the method, has blocks defined in terms of their volume, area of interface with neighbouring blocks and distance from node to interface. In TOUGH2, time is discretised implicitly using backward differences, CO_2 is incorporated and the set of non-linear equations has coefficients which are often strong functions of the independent variables. An iterative simultaneous solution is necessary, and the Newton–Raphson method is used. The programme has automatic step length control; Δt is initially set by the user but is varied automatically to retain accuracy or to avoid wasting computing time.

13.3.2 Reservoir Simulation in Practice

Figure 13.4 shows the general arrangement of a recent model of the Wairakei resource.

The map on the left shows a plan view of the division of the resource into blocks—note that they vary in shape, as permitted by the integrated finite difference method. There are many more small blocks in areas of particular interest. The column on the right of the figure shows the vertical distribution of layers, varying in thickness according to their influence on the results and the degree of interaction with the fluid flow. The model extends to a depth of almost 3,500 m, but the average well depth at Wairakei is of the order of 1,100 m, so most of the production and injection flows take place in formations above this depth and the drilling and well measurements information allows greater definition of the model in this range.

The model is initially constructed using information about the geological formations based on drilling results, coupled with an indication of the area of the resource in plan from the resistivity boundary. Major faults intersecting the resource may be represented in the block structure of the model, although this is not illustrated in Fig. 13.4. A preliminary model of the natural evolution of the resource from emplacement of the heat source up to the relatively steady state of an undisturbed resource is made first. This provides the initial distribution of pressure and temperature and hence fluid state. The results of well measurements to determine the undisturbed reservoir temperature and pressure distributions are next compared with the model results. In the case of a resource which has had many years of production, the most recent well measurements can be compared; careful measurement interpretation is required at this stage, to make sure that internal flows

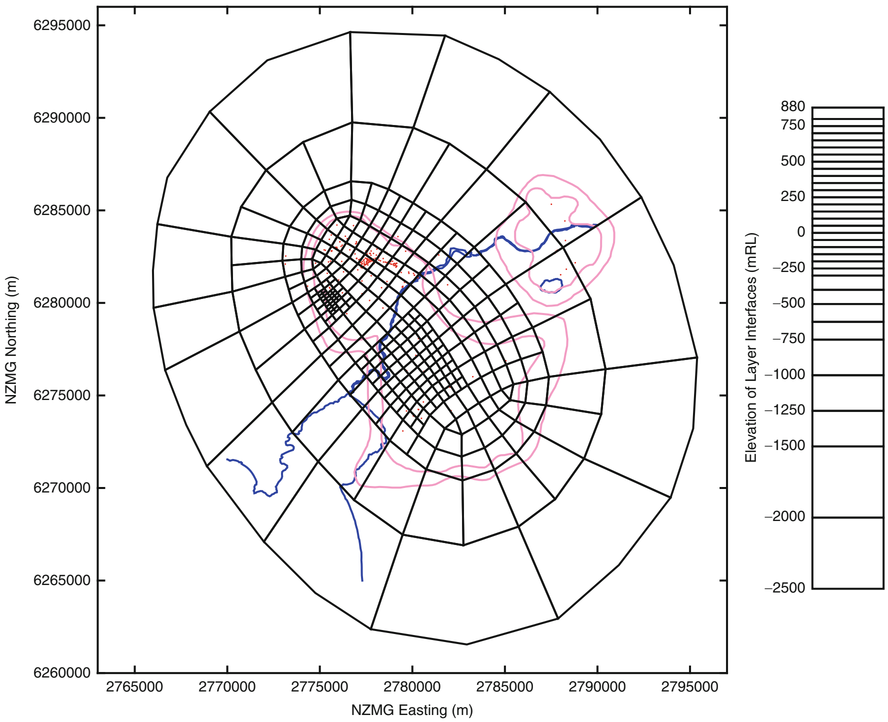


Fig. 13.4 A numerical reservoir simulation model of the Wairakei geothermal resource, using TOUGH2 (*reproduced from O'Sullivan et al.* [2009] *by permission of Elsevier*)

in the well are not misleading. Figure 13.5 shows an example of the comparison between measurements and predictions for a particular Wairakei well. This represents good agreement. Modelling near-surface formations and surface discharges is particularly difficult, perhaps because of the greater diversity of flow paths and material properties close to the surface where lithostatic pressures are relatively small compared to greater depths.

The Wairakei model shown above is the outcome of continuous development since the 1980s, in both simulators and field measurements used as input data, and it is at the extreme end of the spectrum of resource models as regards detail. Numerous examples of models for various fields can be found in the literature for all stages of resource use (see IGA [2012]). The starting point for modelling is an idea of the flow paths available in the resource, both permeable formations and faults, the boundary conditions that influence the flow, perhaps providing an impermeable barrier or very good permeability and hence a constant pressure. This idea of how the resource functions is referred to as a conceptual model—it is the equivalent of a diagrammatic sketch showing the flow paths and heating surfaces in a fossil-fuelled boiler or a piece of machinery. The chemical interaction between the resource rocks and the geothermal fluid is an important feature of any

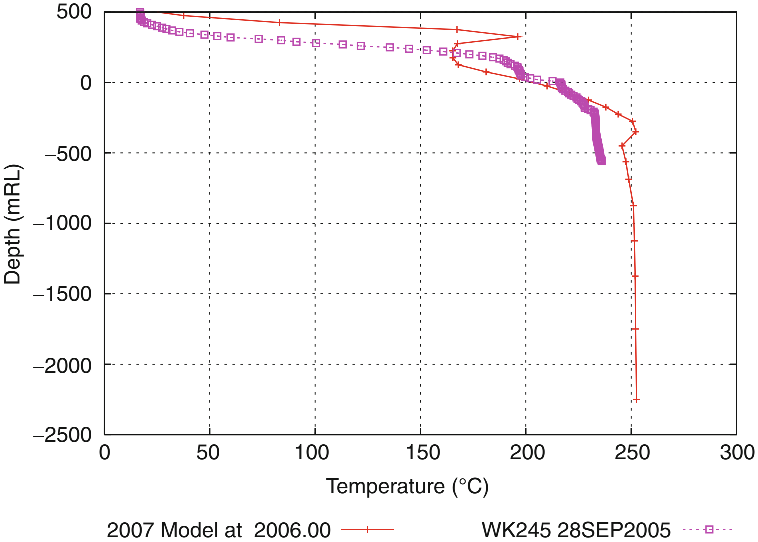


Fig. 13.5 Demonstrating the comparison between vertical temperature measurements in an individual well and model predictions for the block in which the well is located, for Wairakei (*reproduced from O'Sullivan et al.* [2009] *by permission of Elsevier*)

geothermal resource, and sometimes the outcome of this interaction is a modification of the fluid mechanics of the resource, for example, the deposition of solids blocking pores and sealing faults. Chemical interactions and measurements provide clues as to the physical processes taking place and contribute directly to the understanding of the full workings of the resource but currently only indirectly to the conceptual model; modelling including chemical reactions is at the development stage. A change in the concentration of carbon dioxide in solution, however, is a physical change that is routinely modelled.

O'Sullivan et al. [2001] reviewed the state of the art and reported that models with up to 6,000 blocks were being used, with minimum block thicknesses of 100 m and minimum horizontal dimensions of 200 m. They refer to an established method of constructing a model, or more precisely, of adjusting the parameters of the concept to make the simulation reproduce the observed behaviour; this involves running the model from a starting point in the distant past and ensuring that the trend of changes ends up with the distribution of measured variables (pressure, temperature and fluid state) used to arrive at the conceptual model.

It is no fault of modelling that the forward predictions are most reliable halfway through the working life of a resource or beyond and least reliable at the beginning, when the total production and injection amounts are small and the operating history short or even non-existent. Despite this, models are used in the initial planning of a project. Adjustment of formation properties to match the flowing enthalpy of a discharging well has already been mentioned, and O'Sullivan et al. [2001] mention the same approach used with measurements of decline in well output—if there has been insufficient production and injection to result in resource wide changes, the behaviour of individual wells provides the only alternative. The paper notes the difficulty of correctly modelling changes to surface activity.

After about 35 years of development, reservoir simulation is now an essential part of managing the large-scale use of a geothermal resource. The numerical details of the programmes can justifiably remain invisible to the user, and as a by-product, the literature on the topic is more generally readable, focusing on the comparison of measurements and predictions because the physics are correctly represented in the software and the mathematics is reliable. There is always a risk with software packages that because the input data are well defined, it is assumed that once they are provided, no further skill is required. To use a simulator and obtain reliable results requires an intuitive feel for the physics of flow in the resource, together with experience and aptitude.

13.4 The Overall Project Plan

Some information must be available before any large-scale geothermal resource use can be planned for, so funds must be committed without any guarantee that the expenditure will be recovered. These might be referred to as establishment costs. The developing organisation is most likely to have had previous experience in geothermal resource development or be a government organisation set up to initiate resource use. It is likely to have its own qualified and experienced scientific and engineering staff but unlikely to have immediate access to cash at the flow rates needed for a project of even a few tens of MWe, so other parties must be involved.

Staged development is a common way to minimise financial risks. A 25 MWe development may provide enough information in 5–10 years for a second stage to proceed with less risk than the first. Field measurements will have allowed a reservoir model to be developed, and experience will have been gained in dealing with the chemistry of the well discharge. On the other hand, the security of a moderate-sized first stage may cost a premium; the optimum development may be larger. Modular ORC plant will be included in the list of contenders for prime movers.

13.4.1 The Parties Involved

Most often, the development is the work of a single company. Sometimes the arrangement is as shown in Fig. 10.5, where a Resource Company is set up to sell steam to a Power Station Company. In either case, discussions with the Electricity Supply Company would take place early in the planning, to make sure that there is a potential market. The marketability of the electricity generated will depend on the cost of generation, but it is too early to make a proper estimate of this.

Figure 10.5 shows many third party opinions being sought by the developers and the banks. This is because the resource is as yet unexplored—a few wells may have

Table 13.2 Relative cost components for a 50 MWe development in 2007 US$ (*abstracted with permission from a New Zealand Geothermal Association report 2009*)

Cost item	Details	US$ million
Establishment	Geoscientific exploration, resource consents, site preliminaries	2.5
Drilling	2,500 m production well	3.6 per well
	2,000 m injection well	2.9 per well
Steamfield	Dual flash	27
Power station	Single unit, pass-in condensing steam	74
Annual operations and maintenance		2.7 pa

been drilled but not many, because of the need to minimise expenditure of funds if there is no ready way of recovering them. Table 13.2 illustrates the cost components of a 50 MWe geothermal power station development in US$ million, based on a report commissioned by the New Zealand Geothermal Association [2009].

The output of a production well can vary between 3 and 25 MWe, although the upper figure is exceptional, so the number of wells cannot be estimated very precisely.

A first estimate of the type of prime mover most suitable will be made, steam or ORC, and whether there are any major obstacles in the form of difficulty in landing heavy machinery at the available ports, transporting it overland, or problems with the actual siting of the station, bearing in mind local geotechnical conditions and environmental impact. The electricity transmission route will be determined. Such studies will result in short, broadly scoped reports at first, with more detail added as discussions progress.

A financially orientated project analysis will be started, using the methods described in Chap. 10. The banks will lend more easily to a company which has previous experience in geothermal engineering, or at least in the energy supply industry, and also has substantial financial resources and assets so that the loans can be recovered, if necessary by the sale of assets. A long-term electricity sales contract which assures the developer's income is likely to be required. Lenders are generally cautious about new technology, so the plant and equipment, the construction and the operating procedures should all be well proven.

13.4.2 Stages of the Project

The project can be broken into stages. The order is important, but it may not be possible to define it at the outset, so points of no return need to be identified and critical paths. A project team must be set up under the direction of a project manager. On completion of the project, an operating organisation will be required, and the project will be staffed as required during construction, with a view to some construction staff being retained as operating staff. Because every activity has costs associated with it, whether carried out in the field or at a desk, the scheduling of the steps has to be under continuous scrutiny; there will be a final commitment date for every step, after which changes of mind may be costly. A typical list of the steps is shown:

- Surface exploration
- First estimate of resource capacity
- First drilling
- Further drilling after reviews of first results
- Preliminary resource assessment
- Arrange land access or purchase
- Preliminary engineering design
- Seek permissions to develop the resource
- Plan the project, cash flows, activities and decision points and produce a schedule in the form of a Gantt chart
- Make commercial arrangements and seek finance
- Carry out further design, call tenders or negotiate directly with suppliers
- Tender assessment if required and manpower planning
- Carry out baseline environmental surveying
- Start construction site work

13.5 Environmental Impact Assessment

Permits or resource consents are usually required by law before the large-scale use of a geothermal resource is allowed in any country. Environmental impact is high on the list of items to be examined and necessarily involves scientists and engineers but in an unfamiliar role. Chapter 14 provides examples of the interaction between the authorities and the developers in New Zealand resulting from the legislation there. The major environmental impacts of geothermal resource use are by now well known, but some of them are country and resource specific. The remainder of this section introduces the most important ones.

13.5.1 The Effect on Geothermal Surface Features

Surface discharges of hot water and steam are quite rare features worldwide, so they often provide interest for locals and tourists; the natural features and spas of Japan are a good example. Extracting fluid from a resource decreases the pressure within the resource, often resulting in a lowering of the water level. Heat may still break the surface as steam because the rocks above the new water level are still hot, but the chemical composition and appearance of springs may change totally; springs discharging neutral pH chloride water may change to discharging acid pH sulphate water as a result of the upper formations becoming filled with steam and geothermal gases, H_2S being particularly significant. Fumaroles may replace springs. Surface features are valued by scientists as there is a good deal still to learn about the natural evolution of the land in response to the arrival of a pluton and by sections of the

Table 13.3 Comparison of the CO_2 emission rates for various fuel types as quoted by various authors

Source	Coal	Oil	Natural gas	Geothermal
Bloomfield and Moore [1999]	967	708	468	82
Thain and Dunstall [2001]	915	760	345	69–100
Contact Energy [2003]	930		340	10

Units are tonnes of CO_2/GWh

population with an ancestral record of using them for fundamental purposes such as heating, cooking, bathing and a range of cultural activities which rely on the existence of the features in their present general form rather than a particular level of discharge. In some instances, they have already been changed by previous generations. Since surface discharge is a feature common to most geothermal resources, a development proposal must address the effect on them, a difficult task since the fluid mechanics of surface features is difficult to describe in reservoir simulation models. Injection of separated water is necessary to avoid the contamination of waterways and maintain resource pressure, although it is not necessarily sufficient to achieve the latter.

13.5.2 Effect on Global and Local Air Quality

H_2S and CO_2 are produced at the surface where there is geothermal activity, and they are produced at a much greater flow rate by discharging wells. These are non-condensable gases which collect in the power station condensers and have to be continually removed to maintain vacuum. CO_2 is a global warming concern, but both gases can kill in sufficient concentrations and H_2S is noticeable and unpleasant even at very small concentrations.

Various authors have cited the CO_2 output from power stations using different heat sources, and Table 13.3 compares their data.

There are variations due to the efficiency of particular plant and the quality of the fuel. Contact Energy's [2003] figures are for individual New Zealand power stations, the geothermal one being Wairakei, whereas Bloomfield and Moore [1999] show the results of a nationwide US survey. Thain and Dunstall [2001] give the average output from 580 MWe of Indonesian geothermal power plant as 69.2 tonnes CO_2/GWh and 1,124 MWe of Philippines geothermal plant as 94.1 tonnes CO_2/GWh. Electricity generated from geothermal resources produces on average 11 % of the CO_2 produced by burning coal and about 25 % of that produced by burning gas. It has been claimed that geothermal binary cycle plants emit no CO_2, but those that condense geothermal steam in their heat exchangers release the non-condensable gases, often injecting them into the rising plume above the air-cooled condensers.

The gas concentrations in air in the locality of the resource may be of concern. At atmospheric pressure and temperature, CO_2 is denser than air and can be dangerous in confined spaces with only high-level ventilation and in depressions in the ground, but H_2S is much more of a threat in similar circumstances. Wellhead cellars need low-level ventilation, and diggings in the resource area may need to be monitored. At low concentrations, the odour of H_2S can be a nuisance. Fisher [1999] reviewed natural levels in New Zealand and permitting considerations. A concentration of 7 $\mu g/m^3$ is a typical “not to be exceeded” guideline in areas without any natural sources of the gas and 70 $\mu g/m^3$ for those which have, such as geothermal surface discharge areas. He reported that the concentrations in Rotorua, a New Zealand town built over ground with extensive hot spring discharges, are typically in the range 50–400 $\mu g/m^3$.

The evidence presented in New Zealand resource consent hearings usually includes atmospheric modelling incorporating wind measurements at the site. The compressed gases from the condenser are usually discharged from one or more vertical pipes immediately above the cooling towers, within the rising plumes of steam or hot air. The exact location and the format of the cooling towers must be specified for the model, which can be used to choose sites. Background (baseline) readings before development are required. At Ohaaki, the site of the only concrete natural draft geothermal cooling tower so far as is known, discharging the non-condensable gases into the tower has resulted in some acid damage to the reinforced concrete.

13.5.3 Ground Subsidence

Ground subsidence is the lowering of elevation as a result of the compaction of geological formations. Where it occurs, it is a difficult issue to assess because the physical processes taking place are poorly understood. It is not confined to geothermal resource development but has occurred in response to taking groundwater and oil—Bloomer and Currie [2001] reviewed international experience in all three activities. It has been a problem in New Zealand at geothermal development sites. At Kawerau, the geothermal resource was developed in the 1950s as an energy supply for the pulp and paper industry located there. Paper is manufactured in very long lengths by passing through a sequence of rollers many tens of metres in length at high speed. The alignment of the rollers must be precise and stable, but the ground was found to be subsiding in response to fluid production from the wells. The Kawerau subsidence was relatively small and uniform throughout, whereas at Wairakei, it was small and uniform over large areas but extreme in a few localities, as much as 20 m (it is discussed in more detail in the next chapter).

Reddish et al. [1994] addressed subsidence over oil and gas reservoirs and developed a numerical calculation procedure, noting that subsidence requires at least one of the following circumstances:

(a) A significant reduction in reservoir pressure
(b) A very thick reservoir
(c) Weak and poorly consolidated reservoir rocks
(d) A reservoir with a considerable areal extent compared with its thickness

The modus operandi of geothermal developments, up to the fairly recent past, has allowed (a) to occur. Many being composed of stratified eruption debris, circumstance (c) is often met but (b) and (d) less so. Compaction can follow a reduction in pore pressure or a reduction in pore fluid temperature. Geertsma [1973] developed a theory and provided an analytical solution to predict the subsidence resulting from the compaction of a uniform thickness circular disc of compactable material buried at a specified depth. The compaction of the disc allows the overburden to sink, forming a smooth-sided bowl. The edge of the bowl has a bigger radius than the disc, and the size ratio is a function of the depth of burial and compressibility. The compaction of the disc is much greater than the final subsidence. The characteristics of this solution are responsible for Reddish et al.'s circumstance (d), and Geertsma concluded that for subsidence to equal compaction, a reservoir at a depth of 1,000 m would need a surface area of not less than 50 km^2. In summary, wide, shallow subsidence could be formed by localised compaction much greater than the subsidence, in homogenous ground. Geertsma's theory has been applied to geothermal resources, despite their inhomogeneity.

13.5.4 Induced Seismicity

Any faulted and fractured geothermal resource is prone to move (as opposed to compact) in response to thermal contraction and hydrostatic pressure reduction, producing micro-earthquakes, but associating particular events with any degree of certainty to the activities of a geothermal development is difficult. Most geothermal developments are in tectonically active locations naturally prone to earthquakes. Many cases have been cited of micro-seismicity in response to geothermal resource development, for example, Bromley et al. [1983] for Puhagan (Philippines). At the latter, it was reported that during the first few years of production, induced events occurred at rates of about 100 per day, but they then reduced to pre-development levels of typically 1 per day, at magnitudes up to 2.4, which can be felt locally but would cause no damage. Micro-seismicity can be easily monitored. It is not usually regarded as a serious environmental impact.

13.5.5 Effects on Local Groundwater Resources

Several effects are identifiable. Where ground has been cleared of vegetation, for construction, storm water can cause erosion and silting of natural waterways with damage to flora and fauna. Local knowledge and attention to storm water control can avoid problems, and constraining conditions can be defined and attached to permissions to develop a resource.

Large flow rates of contaminated water must be disposed of occasionally, for example, cooling tower ponds may need to be emptied and refilled with clean water, and drilling mud and preliminary well discharge may be held in ponds that must be emptied. In the event of a long power plant outage, injection pipelines must be emptied of separated water to avoid deposition of silica when the water cools down, and the holding ponds must be emptied in turn, to provide for future outages. Ground soakage is often possible in geothermal areas because the groundwater has already been in contact with geothermal contaminants; alternatively, it may be discharged from a lined holding pond into a waterway at a controlled rate at which the concentration of contaminants does little damage. Disposal of the entire separated water production into a river was allowed at Wairakei from the start of production in the 1950s until the present time, although it is about to end under recently renewed resource consents. At Tiwi, Philippines, separated water and condensate were discharged into the sea from start-up in 1979 to the mid-1990s. At Cerro Prieto, Mexico, separated water is reduced by evaporation before being injected. In the present era, many organisations are adopting a zero discharge policy, with deep injection of all liquid waste.

Continuous injection of waste water is not free of problems. Injection is an integral part of extracting as much heat as possible from the resource—it is a way of maintaining pressure and ensuring that heat is transferred from the rock to water, which is more effective because the heat transfer coefficient is higher and the heat capacity of water is greater than that of steam. The resource will have been defined in area from resistivity surveys, and using drilling results, a plan will have been made of which areas to designate as production areas and which as injection areas. Injected water returning to production wells is to be avoided, because it may be cooler and have higher concentrations of dissolved solids. Freshwater may reside over a geothermal resource, perhaps separated by impermeable formations, although total impermeability cannot be assured because geothermal areas are typically faulted. Injection should not result in large increases in pressure because of the potential for contamination of groundwater resources as well as the risk of induced seismicity.

13.5.6 Ecological Effects

Certain species of vegetation have adapted to growing in areas with an above-average surface heat flux and are referred to as thermotolerant species. Since the areas of geothermal surface activity are rare in themselves, thermotolerant species growing there are also rare and considered worthy of protection. Hot water discharge from springs enters streams which may also be sites of thermotolerant species along their length. Reductions in the discharge of water and increase of surface temperature by increase in steam flow combine to reduce the area of habitat for the thermotolerant species, the ground either becoming cool and normal, allowing invasion of less specialised species, or so hot that nothing will grow.

The secondary effects of air and water pollution by geothermal contaminants must be considered in respect of ecology.

13.5.7 The Potential for Significant Effects Due to Noise, Social Disturbance, Traffic and Landscape Issues

The sources of noise vary between the construction stage and the operational stage of the development. Drilling is a significant source of noise which cannot be halted during the night and may last for 4 weeks or more per well. Discharge testing is likely to be noisier for short discharges than for long-term discharge testing, when there is sufficient justification for the installation of more sophisticated silencing equipment. Earthmoving equipment and the noise typical of heavy engineering facilities construction can be limited to daylight hours if necessary. The background noise level of a proposed site would be monitored to form a datum for comparison. During power station operation, the noise from forced draft cooling towers is likely to dominate other sources. It may be possible to reduce noise in neighbouring areas by landscape modifications.

Social disturbance is very site specific. In some developing countries, areas with a high enough population density to make electricity supply beneficial are nevertheless remote. The resource area may be covered in dense forest, and roads cut to allow access by large trucks carrying a drilling rig also allow deeper access to the area by the local populace. Damage to local ecology may follow. Local people used to isolation may be exposed to an influx of workers. Social change would follow electricity supply in any event, but the rate of change may be more abrupt than is desirable.

Traffic problems occur in already developed countries, and the solutions may amount only to widening road junctions to allow safer passage of large vehicles or similar.

The effect of a development on the landscape is essentially the change in view caused by a power station, pipelines, wells and associated steam columns. Land must be cleared to make drilling sites and pipeline routes, but landscaping for appearance is possible.

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