Total Energy

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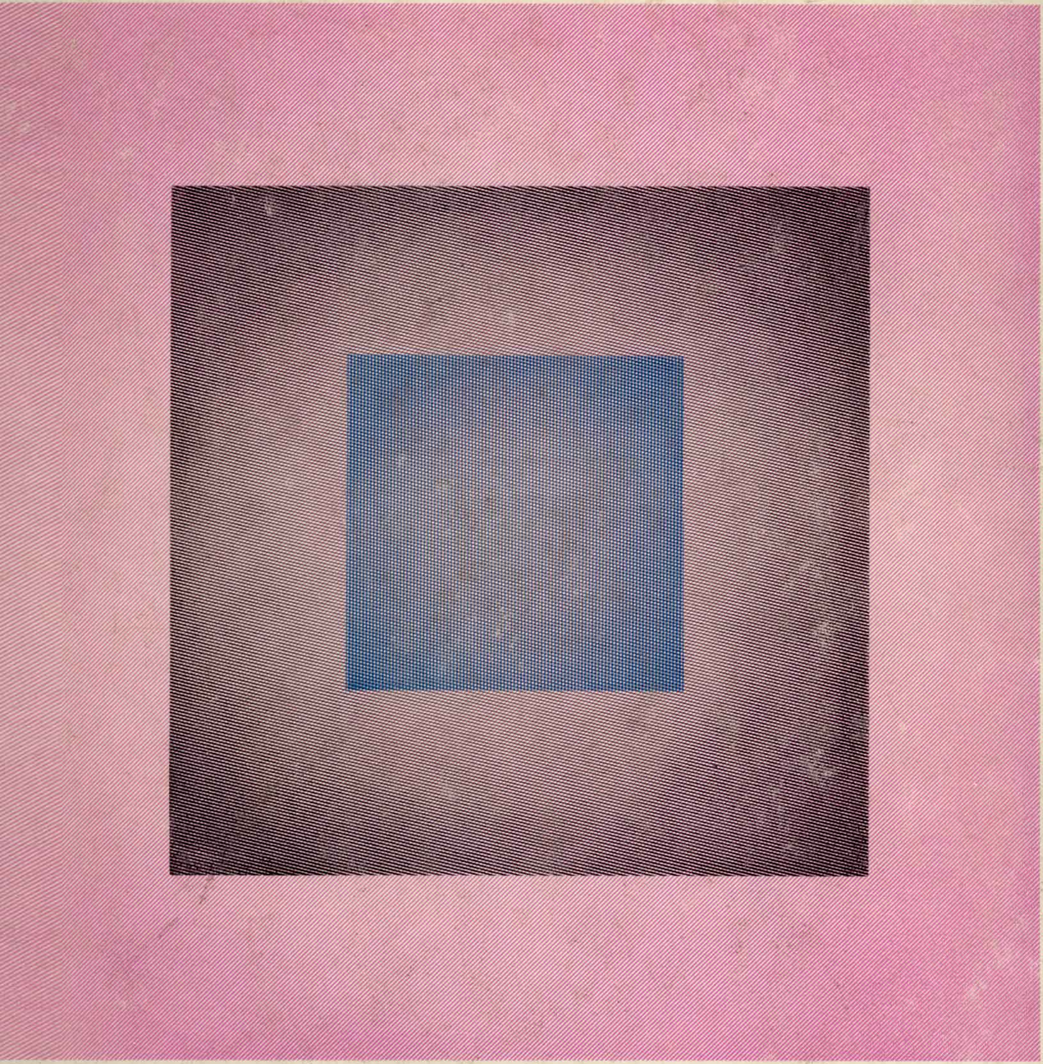

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BY

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VOLUME 6

TOTAL ENERGY

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PREFACE

THE production and distribution of electricity today is an extremely wasteful process. During the conversion of fuel to electric power at centralised power stations more than 60% of the heat content of the fuel is thrown away in unsightly and expensive cooling towers. Distribution of energy in the form of electricity is by far the most expensive and least desirable way of distribution of any public utility due to the need to erect massive overhead powerlines.

It is far better to generate the power where it is wanted and to use the waste heat produced for useful purposes. This is what *Total Energy* is all about. It is a completely new concept. In 1950 the term was practically unknown. Yet every succeeding year now sees an increasing rate of expansion in this very sensible development. The large power-generating companies, too, are realising that they can no longer afford to throw away all their waste heat and they are starting to utilise it in the form of district heating, particularly in Europe.

This book is believed to be the first comprehensive textbook in this new field. Because it is hoped that it will have world-wide appeal, it was decided to give all units in the English system and in the new metric SI (Système International d'Unités). A table of SI conversions is included. To avoid confusion, all money values are given in U.S. dollars, with the date when they applied in brackets, except in one case where Canadian dollars are given instead.

The author would like to thank all the many organisations and firms whose help has made this book possible. He would particularly like to thank his co-authors for their valuable contributions.

University of Salford, England R. M. E. DIAMANT

SI UNITS

(Système International d'Unités)

THE following are conversion factors from English units to SI:

1 inch	= 0·0254 m
1 foot	= 0·3048 m
1 yard	= 0·9144 m
1 in^2	= 645·16 mm^2
1 ft^2	= 0·0929 m^2
1 yd^2	= 0·836 m^2
1 in^3	= 1·638 $\times 10^{-5}$ m^3
1 ft^3	= 0·0283 m^3
1 U.K. gallon (not used in this book)	= 4·536 dm^3
1 U.S. gallon	= 3·785 dm^3
1 lb	= 0·4536 kg
1 lb/ft^3	= 16·019 kg/m^3
1 lb/in^2	= 6·8948 kNm^{-2} = 0·068948 bar
1 psig	= 0·068948 bar (g) = 6·8948 kNm^{-2} (g)
1 Btu	= 1·055 kJ
1 therm	= 100,000 Btu = 105·5 MJ
1 hp	= 745·7 W
1°R	= 5/9 °K
t°F	= 5/9 (t − 32) °C
1 Btu/ft^2-hr °F	= 5·678 W/m^2 °C
1 Btu/ft-hr °F	= 1·7307 W/m °C
1 Btu in./ft^2-hr °F	= 0·1442 W/m °C
1 Btu/ft^3	= 37·258 kJ/m^3
1 ton of refrigeration	= 3·5169 kW

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CHAPTER 1

WHAT IS TOTAL ENERGY?

ELECTRICITY is the most convenient general form of energy. It can be converted at almost 100% efficiency into heat and also at very high efficiencies into mechanical energy, light energy and sound energy. Its great advantage is the ease with which the energy can be led exactly to the spot where it is needed, yet for many purposes such flexibility is scarcely needed.[82, 104]

However, the production of electricity from the combustion of natural fuels, or for that matter, from the heat produced in nuclear reactions is by no means efficient. In the chain of reactions:

Fuel → Heat → Mechanical energy → Electrical energy,

the weakest link is in all cases the conversion from heat to mechanical energy. In even the most perfect system this is limited by Carnot's equation:

$$\text{Eff.} < \frac{T_2 - T_1}{T_2}$$

where T_2 and T_1 are the highest and the lowest temperatures of the system in degrees absolute respectively. In practice T_2 is represented by the maximum gas temperature achieved inside the diesel engine, gas engine or gas turbine, or the maximum saturation steam temperature inside a steam turbine, while T_1 is represented by the temperature of the exhaust gases of a diesel or gas plant, and by the temperature of the condenser water in the case of a steam plant. As exhaust gases in gas turbines and similar equipment emerge at around 1400°R (773°K) while the operating temperatures are seldom much in excess of 1950°R (1073°K) the thermodynamic limitation of efficiency of the heat-energy conversion process with such typical gas turbines is

$$\frac{1073 - 773}{1073} = 27{\cdot}8\%$$

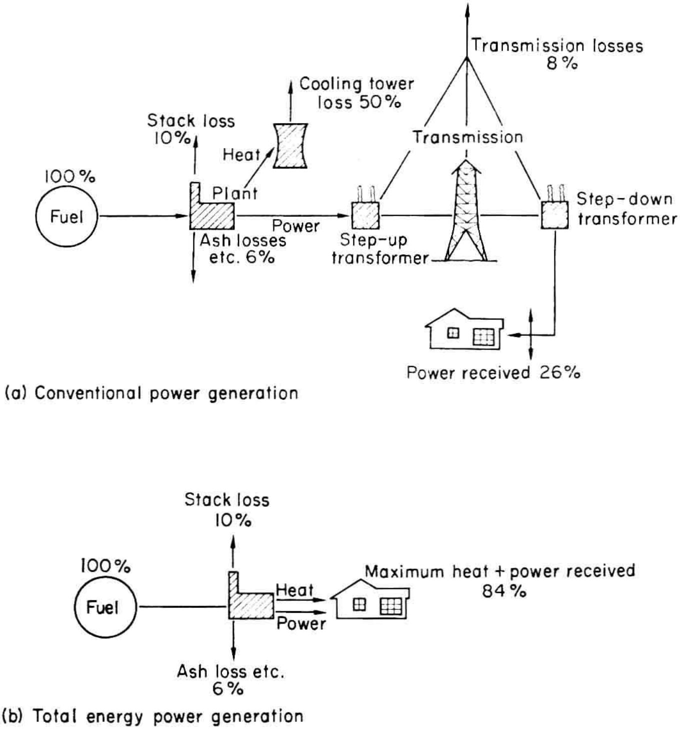

FIG 1.1

It would no doubt be possible to design gas-turbines with somewhat lower exhaust temperatures and somewhat higher combustion-chamber temperatures, but improvements in the overall efficiency of operation would still be marginal.

Steam turbines operate under better conditions. Modern steam plants can operate with steam at up to 580°C (853°K) and exhaust the steam at a temperature as low as 30°C (303°K). The theoretical limit of the conversion of heat into energy with such a turbine is thus:

$$\frac{853 - 303}{853} = 64{\cdot}5\%$$

However, due to the facts that steam as a compressible gas deviates considerably from the ideal gas laws, that it is necessary to superheat the steam to avoid sedimentation and corrosion of turbine blades, and for many other reasons, the actual practical efficiencies of even the most modern steam plants seldom, if ever, exceed about 36–37%. Nor is there much likelihood of much improvement in the future. The lower limit is already set by the high vacuum operated on the exhaust side, which can hardly be improved upon. Better construction materials may make it possible to squeeze a few more pounds of pressure out of the steam boiler, so as to increase the inlet temperature somewhat. However, even this is unlikely to raise the overall efficiency of power generation by more than a few percent at the most.

As far as the older, low steam-pressure steam turbines were concerned their efficiencies were very poor. As recently as 1963 the Oxford power station, operating with a steam feed temperature and pressure of 640°F (340°C) and 250 psig (17·4 bar (*g*)) pressure, had an operating efficiency of only 8·07% while the Ribble A station, another low steam-temperature and pressure station, operated at 5·77% overall efficiency.

Yet, according to the first law of thermodynamics, the total heat input into a system must always equal the total heat (or other forms of energy) output. What has happened to the remaining energy contained in the fuel? It has been converted into heat. Some of this heat, such as the heat lost by radiation from the boiler plant, or lost as sensible and latent heat in the flue gases, it not easily regained, although later in this book we shall encounter a Russian technique of doing precisely this (p. 334). Most modern boiler plants work at efficiencies of 85% and above. In addition, there is a certain heat loss in the turbine bearings and in the conversion process from mechanical energy to electricity, but these factors remain small. By far the largest proportion of heat is lost to the atmosphere either directly, as when the exhaust gas from gas turbines, gas engines and diesel engines is released into the air, or indirectly. When seawater or river water coolers are used to abstract heat from the condenser in which the low-pressure steam from the exhaust side is reconverted into water, or when cooling towers are used to dissipate the heat, vast quantities of energy are wasted. In most cases the quantity of energy so wasted is much greater than the energy usefully converted to electricity. As the temperature of the water fed into the cooling towers is quite low, it is virtually impossible to make use of these large quantities of low grade heat.

TOTAL ENERGY operation seeks to obtain electricity in a way that uses nearly all the energy contained in the fuel instead of only a small fraction of this energy. There are several ways of doing this:[44, 45]

1. It is possible to use large existing power stations which are operated on the ITOC (intermediate take-off condensing) principle so as to obtain a flexible heat/electricity balance. Steam is bled off along the turbine body and its latent heat is used to heat up circulating water to any desired temperature between 200°F and 350°F (93–178°C). Alternatively, the bled-off steam is used directly. The heat is then transported in the form of steam or hot water to urban areas and is used as such for heating and air-conditioning purposes. Cooling towers or other water coolers are still needed and, because of this, ITOC stations do not operate at anything like full efficiency, but they are a good deal more efficient than standard condensing turbines. In addition, operating conditions are better from a general economic principle.

2. It is possible to abandon the grid system entirely and to build small power generation plants as a part of the housing system or complex. These power generators can be small steam-driven back-pressure plants, yielding hot water at a temperature of around 212°F (100°C). This hot water can then be used for space heating or industrial purposes. Alternatively, the types of machines used may be diesel engines, gas turbines, free piston gas engines or stationary aircraft jet engines, which combine a reasonable efficiency of electricity generation with high flue-gas output temperatures. The waste heat can be used for such purposes as space heating, air conditioning, refrigeration, hot-water supply, process heating, sea-water evaporation, etc.

The installation of such plant is particularly popular in the United States where developments have been very rapid during the last few years and where future developments promise to be even more startling. At the end of 1964 there were only 175 schemes in operation in the United States, but this figure rose to 300 by the end of 1966. It is estimated that by 1978 there will be at least 25,000 total energy systems installed in America.

3. At the lowest level, it is even possible to provide total energy to single dwellings. Such plant consists of a petrol-driven generator, or

may in the future be in the form of a natural gas-fired fuel cell, which produces electricity and enables the waste heat produced during the combustion processes to be used for space heating and the provision of domestic hot water.

ADVANTAGES AND DISADVANTAGES OF TOTAL ENERGY OPERATION

Cost of Transportation of Energy[107]

Long-distance transmission of electricity is one of the most expensive forms of transmission of energy known. If one assumes the transmission of the same quantity of energy over the same distance, and if one assigns to power transmission costs by means of an overhead 50 kV cable and auxiliaries such as transformers, switch gears, etc., an index figure of 100, the cost of transmission using other methods is as follows:

Oil in an underground pipeline, including cost of pumping stations, maintenance of pipes, etc. = 27.

Natural gas in underground pipeline = 31.

Hot water at a temperature of between 150 and 200°C using the Soviet single-pipe system including the cost of heat losses, pumping costs, etc. = 48.

Hot water using a flow and return pipeline employing a twin pipeline underground culvert, including heat losses, pumping costs, etc. = 67.

As can be seen, costs of transmission of energy in almost any other form are a fraction of the costs of equivalent electric power transmission. The reasons why electric power transmission is so dear are the following:

(a) It is necessary to use expensive step-up and step-down transformers at the beginning and at the end of the transmission lines, which waste a good deal of power in the form of heat.

(b) There are considerable power losses during the transmission of power. These are in the form of current leakages through insulation weaknesses, conversion of power into heat due to the resistance of the wires, thunderstorms, etc.

(c) The establishment of pylons ruins large areas of land for farming, and naturally compensation has to be paid for this. Underground pipelines do not interfere with farming at all.

(d) Erection costs and repair costs for overhead lines are very high, in contrast to buried lines which, once positioned, can usually be forgotten altogether.

If, however, electric power is to be transported not by means of overhead lines, but as is often suggested by many who object to enormous pylons on amenity grounds, by using buried cables, the cost figure would soar high above the index of 100 given. It has been stated that the cost of running underground high-voltage cables averages about $2·4 million per mile, roughly the cost of running an equal length of a six-lane motorway. Such costs are naturally prohibitive, and in consequence the only feasible way of transporting electric power over long distance would appear to be the overhead high-voltage cable, carried by large pylons. These pylons, apart from being unsightly, interfere with agriculture, constitute a hazard to aircraft, and are liable to being blown down during storms, causing interruption of services and possible hazards to the population. They also often interfere with television and radio reception.

Yet other types of energy can be transported completely conveniently underground, the pipes being virtually totally maintenance free and offering no trouble or hazards at all, except during the brief construction period.

Plant Cost

The individual plant cost of total energy equipment is often higher per unit power output than the cost of large-scale plant at a central electricity station. In addition, if connection to the grid system is to be avoided altogether, adequate stand-by facilities are needed, causing an increased capital expenditure. However, as the practice of total energy has expanded, there has been a trend for equipment to be made more economically, by rationalising some of the production processes. For example, the cost of gas turbines fell by 20% between 1960 and 1966. This trend is likely to continue so that the disadvantage of high capital cost should not weigh so heavily. On the other hand, although extra costs are incurred in providing premises such as a cellar or special substation for the total energy equipment, considerable savings can be made in reducing provisions for running power lines. As the erection of power lines is a mainly manual operation which is unlikely to be cheapened appreciably by mass-production techniques, and as such installations tend to become increasingly more expensive as the density of population increases, trends are again favourable to the total energy concept

Fuel Costs[48]

Small-scale consumers have to pay between 30% and 100% more for the purchase of basic fuels than the price which is charged to large undertakings, although there should be little difference in fuel costs charged to intermediate undertakings such as local authorities operating total energy stations for some of their housing estates, and large undertakings such as electricity boards. Smaller plants certainly do not utilise fuel as effectively as do larger plants. For example, a large, conventional gas-fired steam-generating plant uses 11 ft^3 (0·31 m^3) of natural gas per kWh of power generated, while small scale plants need between 12 ft^3 (0·34m^3) and 17·5 ft^3 (0·50 m^3) per kWh. On the other hand, there are better opportunities for small-scale plants to permit the proper utilisation of the waste heat for various purposes than there is for large plants. If a total energy plant is installed to supply both a housing estate and an industrial consumer, it is sometimes possible to obtain between 60% and 80% total utilisation of the heat present in the fuel. Some large-scale district heating gas turbines operate on such efficiencies, but figures like this are difficult to achieve with even highly efficient steam ITOC plants.

Independence from Grid System

The event which gave total energy its greatest boost in the United States was the catastrophic power breakdown in New York[2, 3] and the New England States on the 9 November 1965. One single faulty power relay at Queenston, Ontario, Canada, started the trouble. The total power flow of 1600 MW into Ontario was suddenly dumped upon the New York system, knocking out the main east–west line of New York State. This caused the entire system to collapse affecting 83,000 square miles and 30 million people. The overall cost to the community of this very large power failure was enormous. Only small isolated areas operating total energy systems were immune and could go on normally. Questions have been asked whether modern grid systems are not becoming too large and involved so that such power failures may take place again. Total energy plants, with adequate stand-by facilities, have been considered to be probably more reliable than the enormous super grid systems, where the breakdown of one major component can affect the entire system.

The power failure particularly affected hospitals as only 75·6% had stand-by generators.

In the United States power lines are frequently blown down by hurricanes and tornadoes, thus interrupting vital power supplies. Total energy installations are almost immune against such natural disasters.

Actual Savings made by the Operation of Total Energy Installations[110]

It can be seen that it is always necessary to determine whether in the case in question total energy operation is more economical than the purchase of electricity from central electricity undertakings, which have the advantage of cheaper plant cost per unit power output and also lower fuel costs. There are three basic considerations which determine whether total energy is likely to be a viable proposition:

(a) The equipment must be employed as fully as possible.

(b) The recoverable heat must be utilised well.

(c) Adequate quantities of relatively low cost fuel must be available.

In general, it is not difficult to obtain at least as good and probably better utilisation figures for small total energy plant, as can be obtained for the plant owned by the large electricity undertakings. Much of the peak loading of centralised plant is due to the need to provide electric power for heating, which can be obtained much cheaper and easier in other ways. If electric power is only needed for purposes such as lighting, mechanical movers and other services, with the exception of heating and cooling, a much flatter power consumption curve is likely to be achieved than the one normal for large undertakings.

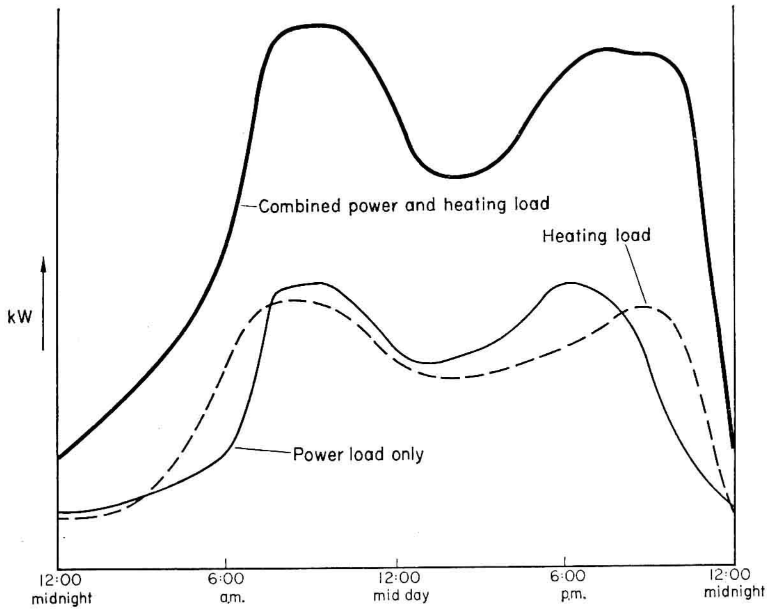

FIG. 1.2. Daily fluctuations of power and heat demand in winter in the U.K.

Good utilisation of recoverable heat is a matter of rather greater difficulty especially in Northern Europe. In the United States this matter is facilitated by the fact that the energy requirements for heating needed in winter are almost balanced by the energy requirements during the summer for air-conditioning equipment.[150] In countries which do not need air conditioning during the summer, such as most Northern European countries, the problem is not quite so easy to solve. Definite steps must be taken to find consumers for the waste heat produced during the summer months. Such consumers may be various industrial undertakings, laundries, dyeworks, chemical works, etc. During the winter months such undertakings would be operating their own boiler plant, to obtain process heat, while during the summer they may be persuaded to purchase waste heat from the total energy plant, provided this waste heat is sold at a price which is lower than the cost of fuel to the undertaking.