Physics and the energy problem

Cheap sources of high-power energy are drying up, but many energy research programmes still ignore the laws of physics—which show the extreme scales that must be adopted by every high-power alternative bar one

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The production, transformation, and conservation of energy are fundamental processes studied by physics. A global energy crisis is now being predicted on the basis of one of the main laws established by physics—the law of conservation of energy.

At present coal, oil, and natural gas are the chief energy resources. The chemical energy stored in them was accumulated by biological processes lasting millions of years. Statistical data indicate that these resources could be exhausted during the next century. Thus, unless we find new sources we shall have to restrict energy consumption, and consequently lower our standard of living.

The inevitability of a global energy crisis has now been recognised. Enormous sums are allocated for energy research and development, but the principal direction of this research is usually selected using very narrow technological criteria. The effectiveness of research increases enormously if it is carried out with a deeper understanding of the basic laws of physics.

Predictions of an approaching crisis are made on the basis of the law of conservation of energy—that is, the "first law" of thermodynamics. Another law which plays a major role in restricting the use of energy resources, however, is the "second law" of thermodynamics which says that "entropy" increases in all processes of energy transformation. Energy is always conserved, but it becomes less and less available for useful work as it passes through its transformations. The waste heat from a car engine, the steam from power station cooling towers, the wake of a ship which is ultimately dissipated as heat, all show the decreasing availability of some initial concentration of energy. Once the fuel is consumed, or energy transformed, the same amount of energy is still there in the world but all, or some, of it has been dissipated into unavailable forms. A source of energy always dissipates itself, and as it does so it increases its entropy. Put in other language, the two laws of thermodynamics veto any solution of the crisis by developing a perpetual motion machine.

The importance of energy density

The development of high-power energy production is restricted by the ways in which energy can flow in nature—by magnetic fields, by electric fields, by water pressure and so on. The particular restrictions of these various fluxes are often ignored, which results in wasting money on projects that can promise nothing in the future.

All the energy processes of interest to us are reduced to the transformation of one type of energy into another, taking place according to the law of conservation of energy. The most widely used forms of energy are traditionally electrical, thermal, chemical and mechanical. They are nowadays augmented by nuclear energy. In every process there is a fuel, a conversion process, and an energy product. For example, in an internal combustion engine these are petrol and air, combustion, and the motion of the piston. Frequently the transformation of energy can be considered as proceeding within a certain volume, with one form of energy supplied into this volume across its surface, and the transformed energy leaving it.

The density of the energy influx is limited by the physical properties of the medium through which it flows. The rate at which energy can be made to flow in a material mediu is restricted by the velocity (v) of propagation of som disturbance (a mechanical wave or heat flow, for exampl and the energy density (U) of the disturbance. The ra of flow (W) is always in a particular direction (it is a vecto like an arrow). Vector W is equal to vector v times U, an proves very convenient for studying processes of energ transformation. The vector was first suggested in 1874, b Umov, a Moscow physicist. A decade later the same vect was introduced by Poynting to describe energy process in the electromagnetic field. Therefore the custom in th USSR is to call this the Umov-Poynting vector.

In the case of a gaseous medium, the vector takes th form of the gas's pressure times the square root of it temperature, multiplied by a constant which depends o the molecular composition of the gas. It determines, fo example, the maximum power that can be transmitt from a burning medium to the surface of a motor pisto or to turbine blades. In this case the power diminish with decreasing pressure. A similar expression determin the maximum altitude at which a turboprop aircraft can fl

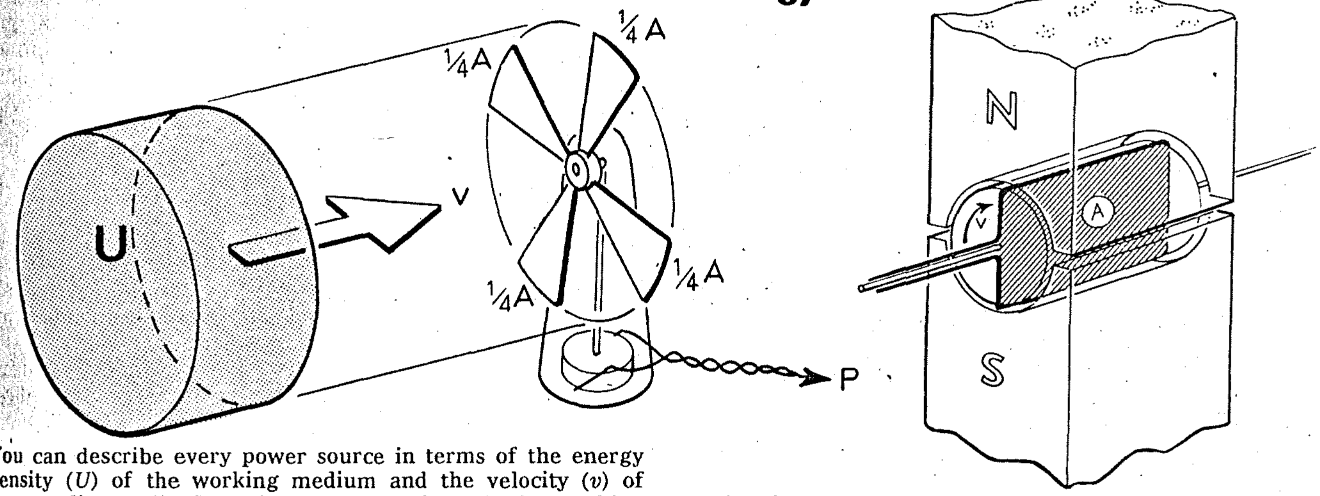
Using the Umov-Poynting vector, we can describe eve those processes in which energy is transmitted by a be drive. In this case the drive power is the product of be velocity and its elastic stress. The maximum power of Van de Graaff generator, in which a belt carries electr charge up to a terminal of high voltage, can be found i the same manner.

I once encountered a technical problem in which the flu of electric energy limited the practical realisation of a idea, under the following instructive circumstances. In th 1940s my teacher, A. F. Ioffe, was constructing an electr static generator which was to feed a small X-ray generato The electrostatic generator was of a novel design an operated very satisfactorily. As a result Ioffe came up wit the idea of replacing electromagnetic generators by ele trostatic ones on a large scale, and basing national pow production on the latter. His basic reasoning was th electrostatic generators have not only a simpler constru tion, but can directly provide high voltage for power tran mission lines. My task was to refute the feasibility of th project by estimating the density of electric energy flu when it is transformed into mechanical energy.

Let us examine the density of energy flux in the electr static and magnetic generators. Energy is transformed i the gap between the rotor and stator of the generat from a mechanical into an electrical form. The veloci v in the formula $W=v \times U$ will be equal to the circumfe ential velocity of the generator's rotor. Design consideration require that this velocity be about 100 metres per secon The tangential forces of interaction per unit area between stator and rotor in the electromagnetic generat are proportional to the energy density in the electroma netic field. This increases with the square of the magnet field strength in a magnetic generator, or the square o the electric field strength in an electrostatic one. (Th constant of proportionality is determined by the generat design.)

Now the maximum easily available magnetic fie depends on the magnetic saturation value of iron and do not exceed 2×10^4 Oersted. When the flow of electric energ is transformed into mechanical energy and back agai we obtain a W of about one kilowatt per square centimetr

The usefulness of energy sources



You can describe every power source in terms of the energy density (U) of the working medium and the velocity (v) of that medium. The flux of energy (W) through the working surface of the source is then the product of the two former quantities $Uv = W$. The final result must be multiplied by factors less than unity involving angles and efficiencies, so W represents the maximum output conceivable. The total power (P) available from a source is equal to W times the working area (A) of the source: $P = UvA$. Physics limits Uv; economics limits A.

Thus for a windmill with four sails of total area A = 80 sq. m area, in a wind of v = 10 metres per second (and thus a kinetic energy density, U, of 50 Joules per cu.m), the maximum wattage is $P = UvA$ is 50 x 10 x 80, or 40 kilowatts. An industry requiring 10 megawatts would need 250 such windmills

Kapitza's heuristic approach also applies to an electric generator. The working area (A) is the area of the moving coil (here taken to be a single loop). The magnetic induction B through the coil creates a magnetic energy density proportional to B^2. And if the velocity of the working side of the coil is v, then the maximum power available is proportional to B^2Av. Kapitza's energy flow viewpoint is an unusual way of looking at electrical power—but it works.

Therefore, for a 100-megawatt generator, the rotor must have a working surface of about 10 square metres.

For an electrostatic generator, on the other hand, the electrostatic field is restricted by the dielectric strength of air—to avoid sparking—and does not exceed 100 electrostatic units. Therefore, in order to produce the same power of 100 megawatts, the electrostatic rotor must have a surface 4 x 10^4 times greater—that is, equal to 4 x 10^5 square metres, or one half of a square kilometre. Hence, the dimensions of high-power electrostatic generators make them unfeasible.

Efficient transformation no answer

A similar analysis shows that we must reject a number of very efficient energy transformation processes for high-power energy production because of limitations on the density of their energy fluxes. For example, in fuel cells, the chemical energy of hydrogen oxidation can now be directly transformed into electrical energy, with the very high efficiency of 70 per cent. But the low rate of diffusion in electrolytes limits its relevance for high-power energy production. In practice, only 200 watts can be produced per square metre of the electrode. The working surface of a fuel cell's electrodes would have to be about one square kilometre to obtain 100 megawatts of power. The capital costs of building such a power plant could not be paid for by the energy generated.

Another direction which might seem highly promising, but which for the same reason carries no future promise, is the direct transformation of chemical energy into mechanical energy. To the frustration of the biophysicists this highly efficient process, which takes place in the muscles of animals, is not properly understood. And, even if it can be reproduced outside living organisms, it will still not be applicable to high-power energy production. The energy flux density will be too low, because it is limited by diffusion processes across the membranes or muscle fibre surfaces. The diffusion rate is no higher than that in electrolytes and, clearly, the energy density of such fluxes cannot exceed, for instance, that in fuel cells.

At present, the new methods of energy generation that attract the most attention are independent of the amount of energy stored in various fuels over the past centuries. The direct transformation of solar energy into electrical and mechanical forms on a large scale is one of the most attractive. But again the practical application of this process for high-power energy production is influenced by a limited energy density. Optimisation calculations indicate that the power yielded on average by one square metre of Sun-illuminated surface will not exceed 100 watts. Therefore, to generate 100 megawatts, electrical energy must be collected from one square kilometer of surface. Not one of the solar energy systems put forward to date justifies its capital cost by the energy generated. These costs must be cut considerably to make it a paying proposition. Therefore the direct exploitation of solar energy on a large scale is not practically feasible. The transformation of solar energy into chemical energy, which has been going on since the beginning of time with the help of plants, remains workable, however. We cannot exclude the possibility that in time this route will be exploited using a photochemical reaction to convert solar energy into chemical energy more effectively and more simply than is now done in nature. [Professor Kapitza is being prophetic here; a success of this very kind was described in these pages a few weeks ago—see *New Scientist*, vol 70, p 651, *Ed.*] Chemical accumulation will have the advantage of enabling solar energy to be used regardless of any changes in its intensity during the day or year.

Geothermal energy is another source being discussed these days. It has been successfully exploited on a small scale in a number of volcanic areas of the world. Geothermal energy has substantial advantages for high-power energy production. The energy resources, although they can be exploited too fast for thermal recovery to keep pace, are, to all intents and purposes, inexhaustible; in contrast to solar energy, which not only has diurnal fluctuations but also depends on the time of year and the weather, geothermal energy can generate power continuously. Parsons, the inventor of the steam turbine, was working on a project to use this energy at the beginning of the century.

The modern approach to geothermal power is based on the fact that between 10 and 15 km under the Earth's crust, the rock temperature is several hundred degrees centigrade. This is high enough to produce steam and generate power efficiently. But in putting such projects into practice we again come up against restrictions related to the energy flux density. The thermal conductivity of rock is very low. The supply of enough heat to the hot water, with the small temperature gradients that exist inside the Earth, must involve large areas—a taxing requirement at a depth of 10 to 15 km. So the feasibility of heating the necessary amounts of water is still doubtful.

A need for nuclear explosions

Several interesting proposals have been advanced now in this field. For example, atom bombs may be exploded at these depths to create either a large cavity or a lot of deeply penetrating cracks. Such a project would be very costly, but I believe that, because of the importance of the problem and the significant advantages of geothermal energy, we must take the risk and go ahead with this project.

Apart from solar and geothermal energies, which leave the sources intact, we also have hydraulic energy obtained by damming water flows (rivers or ocean tide flows). The gravitational energy of water, accumulated this way, can be efficiently transformed into the mechanical form. At present the use of hydraulic energy comes to no more than 5 per cent of the net energy balance, and no increase in this share can be expected. This is because damming rivers is profitable only in mountainous regions, where the potential energy per unit area of the reservoir is high. Damming rivers with a low water head usually is not economically sound, especially when it floods arable soil. The crop is usually considerably more valuable than the energy produced. Here again energy density is insufficient.

The use of wind is also economically unjustified due to insufficient density of energy flux. Of course, solar energy, small water streams, and wind-driven units may often prove useful for small-scale domestic needs.

From the above analysis, it is clear that in the case of high-power energy we cannot find a way profitably to replace the natural resources of chemical energy that are currently being depleted. We must obviously use these energy resources with greater care. However, all such economy measures can only slow down the depletion of fuel resources. They will not prevent the crisis. So it has been generally acknowledged that the solution of the world's energy crisis depends on using nuclear energy. Physics provides a firm basis for this conclusion, as I shall describe in my second article. □

White hope or white-wash in Manila?

Was the Philippines 'Survival of Humankind' experiment just a showpiece or is the country really harnessing technical resources for an attack on underdevelopment?

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Too many Third World countries bemoan their poverty in international forums only to sweep beggars and other unsightly citizenry from their streets when their turn comes to host an international get-together. For this week's IMF/World Bank Conference, the image conscious regime of Philippine President Ferdinand Marcos and his first lady Imelda went a step further. Apart from the routine painting of public buildings, residents of Manila's miserable squatter slums unfortunate enough to face a main road received instructions to paint their shacks and shanties. For the recalcitrant, the army was available to do the honours—at a price.

For hundreds of families crammed next to the Del Pan bridge near the centre of the city, these measures were not enough. Even after they had lowered their ramshackle homes and painted the roofs so as not to offend the sensibilities of passing motorists, the authorities decided that they were still too conspicuous. So at the beginning of last month, the residents were turned out and at least 300 homes demolished.

All this of course, in honour of the World Bank whose stated objective over the last few years has been to help the poorest of the world's poor.

The contradictions run deeper. The Manila meeting of the World Bank is being used as a focus for the protests of religious and political groupings opposed to the excesses of the Marcos regime. One issue concerns the fate of the slum dwellers of the Tondo foreshore, only a few miles from the site where the new international conference and trade centre has arisen in a waste of reclaimed land.

The redevelopment of the Tondo foreshore is a major project of the Marcos government. Part of the redevelopment was the subject of the controversial international design competition associated with the Vancouver Habitat conference. The plan is to build a container and fish port and housing facilities for displaced residents. The plans are opposed by a coalition of local community groups such as the Zone One Tondo Organisation (ZOTO). They say that the plans will cause a massive disruption of the community; that they give no security of tenure since all land will be leased by the government which had formerly promised to grant title to the residents. The cost of the 5000 units of housing already provided—100 Pesos/month rent and down payment of 3000 Pesos in a community with an average household income of 300 Pesos/month—is out of reach of squatters in what is said to be Asia's largest squatter slum.

The World Bank is financing half of the $65 million project cost, so in a move calculated to embarrass the Marcos government, squatters' organisations have called on Robert McNamara, the Bank's president, to meet those leaders of ZOTO and other groups who are not underground. After all, they point out, the World Bank is committed to people's participation in planning.

Since these protests are admitted to be part of the wider opposition to the martial law government of President Marcos, it is difficult to assess how deep the objections really run. The other side of the problem however is to gauge the sincerity of the Marcos government's attempt to deal with the pressing problems of poverty and underdevelopment confronting the Philippines.

The presidential couple are fond of impressive projects—preferably those which are good for the image of the Philippines as leader of the South East Asian ASEAN countries. For the cynic, it becomes difficult to distinguish between the image-building and the real development work.

Just last month, the grandiosely titled "Survival of