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SCIENCE

Energy and Resources

A plan is outlined according to which solar and wind energy would supply Denmark's needs by the year 2050.

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By classifying resources according to their properties, for example, as metals, semiconductors, and insulators, one can obtain broad groups of substitutable materials that are present in the earth's crust, including the water of the oceans, in quantities that probably exceed any foreseeable requirement by man. If one can assume that the use of a resource will rarely result in its being removed from the earth into space, then the term usage will at worst imply dilution to the average concentration of the resource in the earth's crust. Thus, the absolute degree of resource depletion is of minor relevance; rather one must expect to spend an increased effort, related to cost, in order to recover the resources from still lower grade deposits. If used raw materials were returned at maximum dilution, the cost of recovering new raw materials would increase as a function of the integrated usage over the past.

According to Dunham (*1*), for example, the easily accessible deposits of several raw materials may last only 20 to 100 years at the present rate of usage. Thus, it seems reasonable to assume that some groups of resources will undergo sizable cost increases within the time span considered in current planning. The cost of a resource that is extracted by recycling processes will depend on its concentration in the product that is recycled. Today the concentration is often low because of mixing of wastes of different composition. However, if usage of the resource is expanded, the amounts required beyond the recycled quantities must in any case be obtained from the earth's crust at increasing cost.

Energy resources have a particular role in man's activities. The earth receives a continuous flow of energy from the sun, and from solar radiation are derived other energy forms such as wind, currents, and sea temperature gradients. Only minute fractions of these free energy flows have been utilized by man up till now. Instead, mankind exploits finite energy resources such as coal, oil, and fissile material which have been accumulated over periods much longer than it is taking man to deplete them at present rates of consumption. Because the chemical and nuclear energy stored in these resources is released by usage, there is no possibility of recycling. The use of breeder reactors for producing nuclear energy will constitute a type of recycling, but such breeders will still involve resource depletion, for example, of uranium-238.

Energy Policy in Industrialized Countries

Associated with the life-styles of industrialized countries is a strong dependence on manufactured goods with comparatively short lifetimes. Because of the increasing costs of extracting new raw materials and energy from nonrenewable sources, the production of such goods will follow a growth curve of the A type shown in Fig. 1a (*2*). The contribution from the recycling of used goods, shown in Fig. 1b, is included in Fig. 1a. The amounts of change in the level of production and recycling of raw materials are determined from the average profit over 25 years (rather time units) of continued production at the same level.

If the cost of raw materials were to increase while energy prices remained constant, as they might do if energy production by nuclear fusion became safe and acceptable to society, then the production curve would become S-shaped and approach a constant value instead of declining after the peak. However, today's energy policy cannot be based entirely on the unproved potentials of a future resource, and it is necessary to consider the potential of the continuous energy sources. As also shown in Fig. 1, the existence of a continuous flow of energy, of which a fixed amount can be utilized at constant cost (in practice, the ceiling may be far lower than, for example, the total solar energy input), leads to a stable production level. This is preceded by an overshoot phase, when the accumulated use of raw materials is still low, and an adjustment phase, when the recycling is augmented and approaches its maximum value.

In addition to considering the possibility of physical constraints on continued growth of energy and resource consumption, one should consider the constraints imposed by the interconnections between structural changes in society, the systems in use for production and energy conversion, and the economic growth rate with its fluctuations. For instance, the amount of energy spent on raising the gross national product (GNP) by one unit is widely different in different parts of the world. During the last 20 years, Europe and Japan have used only half as much energy as the United States to increase their GNP's per capita by one unit. This indicates a lack of universal relationship between energy consumption and economic growth. Furthermore, it is recognized that the GNP provides a poor measure of the standard of living or quality of life because it includes any activity in society, regardless of whether it benefits that society or not. Statistical data show that in most countries there has been no decline in the amount of energy spent on each new unit of increased GNP per capita. There is evidence that the improvement of living standards (basic needs and luxury) constitutes a diminishing fraction of each new unit

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of increased GNP per capita; the rest is spent on the structural changes required by the growth itself, on its side effects, and on managing its wastes.

Following this line of thinking, I suggest that the traditional manner of growth, characterized by diminishing returns related to the quality of life, should be replaced by our implementing a policy aimed directly at stimulating growth that will improve the quality of life. This again requires that society increase its influence on the types and durability of goods that are manufactured (for example, by changing tax policy). It also places the choice of production and energy conversion systems in a new perspective that may be summarized by such questions as: "Which system would be most compatible with the formation of a society in which the largest possible fraction of the GNP would be placed at the direct disposal of the population, instead of its being absorbed by the structure of the system itself?"

Many nations might find that, compared with nuclear power, the renewable energy sources such as wind and sun, which favor decentralized utilization, would facilitate development in the direction of placing more emphasis on the quality of life. This is partly because the reactor industry gives priority to large units and partly because of the uranium supply situation. A nation without uranium mines or without uranium enrichment facilities might fear that the monopolization of uranium supplies outside its control could result in steeply rising fuel costs after it had made a commitment to a number of nuclear reactors. This dependence on an outside uranium supply and nuclear technology is more serious than a dependence on an outside oil supply, because the capital costs of nuclear reactor plants are larger than those of equivalent oil-fired plants. The large amount of capital that would be invested in nuclear energy production would prohibit a swift change to an alternative energy source, should the uranium supply or the safety issues demand such a transition.

Compared with nuclear energy, the harnessing of solar or wind energy requires equipment designed on a different technological scale. Such equipment is less exposed to monopolization than that for the nonrenewable energy sources, which is one additional reason for suggesting that, in making its energy policy, any nation should keep the continuous energy sources well in focus. The first step toward establishing a policy favoring renewable energy sources will be to evaluate the potential of various regions for solar and wind energy. In general, the renewable energy sources are considerably more equitably distributed over the world than the nonrenewable resources. I will attempt to make such an evaluation specifically for Denmark, a country which, excluding Greenland, has practically no nonrenewable energy sources and which, since World War II, has developed a 90 percent dependence on oil from the Middle East.

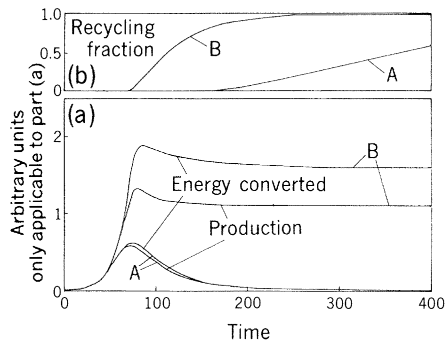

Fig. 1. A simple model of industrialized production. (a) In alternative A the price of new raw materials and energy from nonrenewable sources increases in proportion to the accumulated use. In alternative B the option of using a finite amount of continuous energy sources at constant cost is added. The contribution from recycled used goods, shown in (b), is included in (a).

Potential Energy Resources of Denmark

The average input of solar and wind energy in Denmark is shown in Fig. 2 (*3*). Fluctuations in the wind energy through the year are favorably correlated with the need for space heating, as well as with the variation in electricity use, particularly on the west coast. Solar input is at a minimum in November, but is high in the cold months of February and March when a south-facing, vertical area is considered. The less favorable correlation between solar input and heating requirements during December and January would necessitate the use of additional collecting surfaces in these months, but these surfaces would remain largely unused during the rest of the year.

To evaluate Denmark's total potential of solar and wind energy, one would have to choose a reference height interval for the vertical collectors and establish how close together they could be placed without shading problems. If one used as a reference a 50-meter-high collecting area for either sun or wind energy, there would have to be a distance of about 1 kilometer between solar collectors to allow for shadow lengths in December; the restoration of the wind profile behind a series of 50-meter-high windmills would require about 2 kilometers between rows of mills (for example, if the mills were arranged in rows from north to south to allow for the prevailing westerly winds) (*4*). On the other hand, the spacings perpendicular to the wind direction may be quite small. For the total area of Denmark, 44,000 square kilometers (Greenland excepted), this leads to reference collection areas totaling 2200 square kilometers for solar panels and 1100 square kilometers for windmill swept areas, corresponding to a yearly average of 285 gigawatts of solar energy and 310 gigawatts of wind energy. For the critical months, the solar energy reaching these panels would on average amount to 167 gigawatts (December) and the wind energy to 300 gigawatts (February). Fluctuations between years might alter these values by as much as a factor of 2. For comparison, the average total energy consumption in Denmark is now about 20 gigawatts.

The fraction of the energy estimates made above that could be utilized with known technology would be determined by the efficiencies of the collection and conversion systems. Optimal efficiencies on a yearly average basis are, at present, about 50 percent for solar heat collectors, 5 to 20 percent for electricity-producing solar cells, 40 percent for windmills producing d-c electricity or heat, and 30 to 35 percent for a-c generating windmills that are forced to run at constant angular velocity. Thus, on the basis of the collection areas required, the use of wind energy should be favored for electricity production and possibly also for heat production. However, windmills may require building restrictions in all directions, whereas solar panels can be placed directly on south-facing walls or roofs of buildings.

Solar Energy Systems

The solar heat system I have in mind would consist of a collector (a black absorber with a multilayered glass cover which might be coated to reduce reflection and retain long-wavelength radiation) and a storage tank containing water, salt, or gravel. The storage tank would have a capacity of about a month's usage, and could be common for an entire building block (placed underground), in order to save insulation area. To allow for winters colder than usual or with less sunlight than usual, a cheap auxiliary energy-producing system would have to be added, for example, a system for heating the material in the storage tank by electrical resistance. Solar heat panels of the type described here are estimated to cost up to $100 for each square meter, depending on the scale of production (1974 prices are used throughout this article). The cost of a storage system equivalent to 1 cubic meter of water per square meter of solar collector could probably be covered within the figure mentioned.

The economic assessment may be based on a comparison of the cost of the solar collector with the expenditure that would be necessary to generate, by fossil fuel, the same amount of energy as the solar energy system generates over its lifetime, say 25 years. In order to make these two costs comparable, they must be referred to the same time. This is achieved by transforming the future fuel expenditures into a so-called "present value," which is the amount of money that, together with the accumulated interest, would allow payments to be made annually, each payment being adjusted for the actual fuel cost for that year.

Because I am using 1974 prices, the interest and possible fuel cost increase are corrected for inflation. For simplicity the maintenance costs of the solar and fossil fuel systems are assumed to cancel each other. I will consider two alternatives: (i) the interest (corrected for inflation) is 5 percent per year, and the fuel price stays fixed; (ii) the interest is 5 percent per year and the fuel price increases by 5 percent per year. There is a third important alternative, that both interest and fuel price increase are zero, but it gives results identical to (ii).

The two alternatives of fuel price development could be realized by there being either an increase due to the supply and demand situation described earlier, or a fixed cost achieved by political pressure. The alternative of nonzero interest is based on there having been, in the past, marked fluctuations in the difference between the market interest and inflation, with the two most recent decade-averages being close to 5 percent and 3 percent per year, for Denmark. However, the magnitude of the yearly interest should not be allowed to play a decisive role in the long-range planning of a nation. Thus, an energy program with high investment and low operating cost might be subsidized, for example, through low-interest governmental loans, in such a way that the effective interest becomes zero. This is the other alternative concerning interest.

Today, most heating in Denmark is provided by oil-fired boilers, operating at an efficiency of about 65 percent. If one takes the price of fuel oil in Denmark for 1974 to be 54¢ per gallon (12¢ per liter), then to produce 1 kilowatt-hour of heat per year for 25 years, the cost of the fuel, taken as the present value defined above would be 26.5¢ according to alternative (i) (fixed oil price) or 44.7¢ according to alternative (ii)

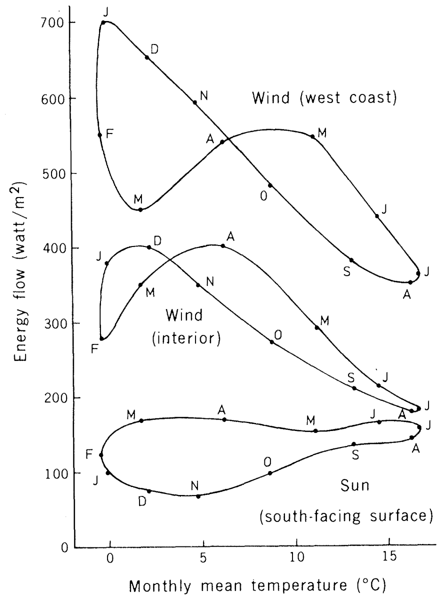

Fig. 2. Monthly average energy flow from continuous sources through a vertical square meter in Denmark, as function of the monthly mean temperature. The sun's height over the horizon at noon is 11° at winter's solstice. The wind data are taken 25 meters above smooth ground.

(either increasing oil price or both zero interest and zero fuel price increase).

The alternative cost of a solar panel which on average will produce 1 kilowatt-hour of heat per year is 17.6¢. However, this should be divided by the fractional usage time of the solar energy system, which is the fraction of the energy collected that can be utilized if the collector size and energy storage capacity are dimensioned so that the heating requirements can be satisfied any time during the year (or nearly any time; that is, there should be negligible use of auxiliary electric heating).

For hot water production alone, the requirements are fairly constant throughout the year, and one typically finds a fractional usage time of 0.76, corresponding to a cost of 23¢ for 1 kilowatt-hour per year over 25 years.

For space heating the fractional usage time lies between 0.2 and 0.5, depending on such factors as insulation and the compass direction of windows. For a combined hot water and space heating system, the fractional usage time can be kept above 0.5, leading to an average cost of 35¢ for 1 kilowatt-hour per year for 25 years.

Wind Energy Systems

Wind power may be based on decentralized systems of windmills or on more concentrated windmill rows, typically arranged in north-south directions in order to avoid the shadowing effects caused by the prevailing winds that blow from the west on the west coast of Denmark, and from the west or east in the interior of Denmark. The 1974 cost of a 200-kilowatt experimental a-c producing windmill with fixed blades, which was tested around 1960 at Gedser, Denmark, is estimated to be \$260 per square meter of swept area (*5*). Its efficiency was about 25 percent, but this was because its gear was not optimal, and if this was improved, the efficiency would be about 33 percent. Windmills with adjustable blades have reached higher efficiencies, but the improvement has not outweighed the higher cost (*6*).

A 1973 report indicates that a-c generating windmills with vertical axes can be built with efficiencies only slightly below those of the conventional mills with horizontal axes (*7*). Because of their better stability during storms, the vertical axis mills may be preferred for large-scale projects. If only heat production is needed, the angular velocity of the mill can be allowed to adjust itself to the wind, and the electric generator can be replaced by a heat generator (for example, of the friction type, based on the formation of turbulence in a fluid). The cost of such mills may, according to some estimates, be as low as \$65 per square meter (*8*). Some authors have even quoted prices as low as \$30 to \$40 per square meter for either vertical axis rotors (*7*) or one-bladed horizontal axis rotors (*9*).

I will assume, in agreement with the conclusions reached at the recent Stockholm meeting (*9*), that a price no higher than \$200 per square meter is realistic for large-scale application, and that the mills have an efficiency of 35 percent for heat production and 30 percent for a-c production. The cost of 1 kilowatt-hour per year over 25 years then amounts to 23¢ for heat and 27¢ for a-c electricity in eastern Denmark, or 13¢ for heat and 16¢ for a-c electricity on the west coast. As in the case of solar energy, these figures must be divided by the fractional usage time.

For heating purposes, windmills are likely to be placed in the interior of the country, and to be equipped with an energy storage system of the same type as for solar energy. With a fractional usage time of 0.7 for hot water production the cost becomes 32¢ for 1 kilowatt-hour per year during the lifetime of the mill, say 25 years. For both hot water and space heating, the fractional usage time becomes high, 0.8, and the cost 29¢ for 1 kilowatt-hour per year over 25 years.

In summary, the production of hot water by solar energy is competitive with production based on oil, even with high interest and fixed oil prices, whereas the feasibility of space heating by sun or wind on a

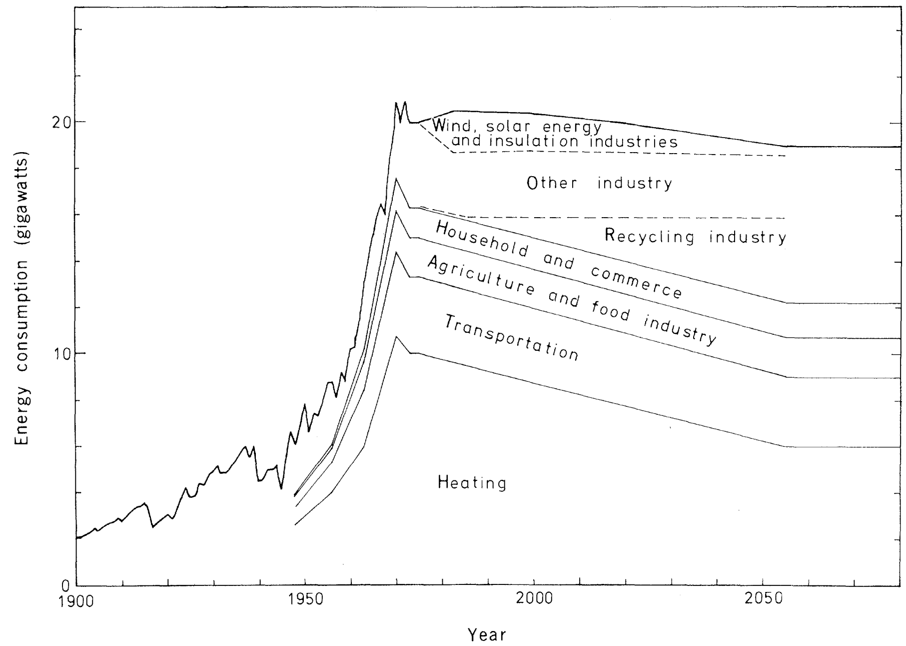

Fig. 3. Net energy consumption in Denmark, shown according to end uses. Up to 1974, actual data are presented (*14*) (yearly averages are given for every year; however, for subdivisions the data are available only for selected years and the corresponding points have simply been connected by straight lines). After 1974, the data show the proposed plan for a transition to a constant level of energy consumption (see text for more details). Energy for heating is shown as a separate entry and is thus excluded from the individual sectors, such as household and industry. Similarly, transportation is taken out of the individual sectors and listed separately. By net energy consumption it is understood that losses during gas and electricity production and exports are omitted. However, waste heat and fuel discarded after incomplete burning at the end-use stage are still included.

strictly economic basis requires low interest or increasing oil price. For the combined production of hot water and space heating, the windmills are cheaper than the solar collectors, under Danish conditions, but both are economically sound and other criteria for choosing the system may be added.

For electricity production I assume for the moment that the electricity generated by the wind would constitute only a small fraction of the energy flowing through the a-c net into which it would be fed. In this case no storage facility would be required, and the price would be given directly by the average power, amounting to 27¢ (16¢ on the west coast), for 1 kilowatt-hour per year over 25 years. Here the west coast figure of 16¢ might be the relevant one. Typical fuel costs for coal- or oil-fired power plants in Denmark lead to corresponding present values of 27¢ and 45¢ for alternatives (i) and (ii) of fuel price development (based on a 1974 fuel price of $1.60 per gigajoule). If the total electricity requirements did not increase, most of the average usage could be covered by windmills without storage facilities, since the existing production apparatus (in particular the gas turbines) could be used to provide auxiliary power.

For comparison one may look at electricity produced by means of fission reactors. According to a recent estimate (*10*), capital costs of nuclear power amount to $702 per kilowatt and the variable costs to 0.435¢ per kilowatt-hour. Based on the fractional usage time of 0.8 (see *10*) (for a power plant running at base load) the production of 1 kilowatt-hour of electricity over 25 years amounts to 16.4¢, if one calculates the present value using a 5 percent yearly interest in fixed prices. The actual cost may be higher for a number of reasons: (i) Nuclear fuel prices may increase; for a 5 percent yearly increase, the electricity cost would be 19.5¢. (ii) Fractional usage times may be less than 0.8; Comey quotes the figure 0.54 (*11*), which leads to a cost of 21.2¢ per kilowatt-hour per year over 25 years, with fixed fuel prices. It should be noted that the low capacity factors quoted by Comey are partly due to restrictions on power output imposed by authorities. (iii) The depreciation time may be shorter for nuclear reactors than for windmills, because of their greater complexity and their being subject to radiation damage, for example. If the depreciation time were only half as long, the capital requirement would increase by 50 percent. We see that wind power (produced on the west coast of Denmark) in any case is competitive with nuclear power, and is probably even substantially cheaper.

So far I have assumed that, during an initial phase, wind-based electricity production would never exceed the demand, so that the wind power systems would never be idle, and no storage facility would be required. The same assumptions were made for nuclear power in the economic comparison. In connection with large-scale electricity production by wind, suitable storage systems would have to be added. The topography of Denmark is not suited for pumped water storage, but underground compressed air storage and possibly flywheel storage might be applicable (*12*). Such storage systems already appear to be economically feasible in connection with fuel-based electricity production. A compressed air storage system is being constructed in Schleswig, just south of the Danish-German border, and another is being seriously considered by the Electricity Company of Western Denmark, utilizing the salt domes abundant in Jutland's underground (*12*). For night-to-day storage systems a cost of $117 per kilowatt, which would correspond to 8 percent of the cost of the windmill, has been estimated for a compressed air power unit that could replace the average power of the windmill. Per kilowatt-hour per year this amounts to 1.3¢, to be added to the 16¢ for the mill itself. The actual cost may be somewhat larger, because of the need for larger air storage volumes in connection with windmills, but as long as natural salt domes can be used, the excavation cost is not decisive.

Energy Requirements

Estimates of future energy consumption will, to some extent, require a model of future life-styles. Changes in life-styles that cannot be anticipated at present will thus be excluded. I shall base my estimates on a few expected changes in life-styles plus the assumption that increased effectivity of energy conversion will be pursued as a worthwhile effort.

From World War II to 1970 the energy used in Denmark for heating has increased exponentially because of a strong effort to catch up with a housing deficiency and because of increased room temperatures. Future increases in energy consumption for heating would be directed toward improving housing standards that are already quite high, and would therefore be less marked. At present, heating requires an average of 10 gigawatts, and the Danish population is 5 million. For simplicity I shall consider a total of 2.5 million building units, each using 4 kilowatts (yearly average) for space heating and hot water. These units are defined as average family dwellings (three-room apartments or houses plus bathroom and kitchen) or building sections, all with equivalent heating requirements; 1.6 million of these units are used for living, and 0.9 million are used for commerce and industry. Had all of these units been insulated to the best of present standards, the average power requirements per unit would be 2 kilowatts (800 watts for air exchange; 600 watts for losses through walls; and 600 watts for hot water)—that is, only half of the present value. According to my plan, there would be a gradual replacement of most of the present units with optimally insulated ones during the next 75 years. On the assumption that a slight increase in the number of units will be needed (for example, to allow for population increase), say to 3.0 million units each requiring 2 kilowatts, then the energy requirement for heating in the year 2050 will be 6 gigawatts. The size of the unit may also be assumed to increase (the average size of a dwelling becoming four rooms, exclusive of kitchen and bathroom, or 120 square meters of floor area), with some changes in the energy balance: 800 watts for air exchange; 800 watts for heat losses through walls; 1000 watts for hot water; but a gain of at least 600 watts from unshielded, south-facing windows, indoor activities, and possibly heat exchangers recovering heat from return air and water.

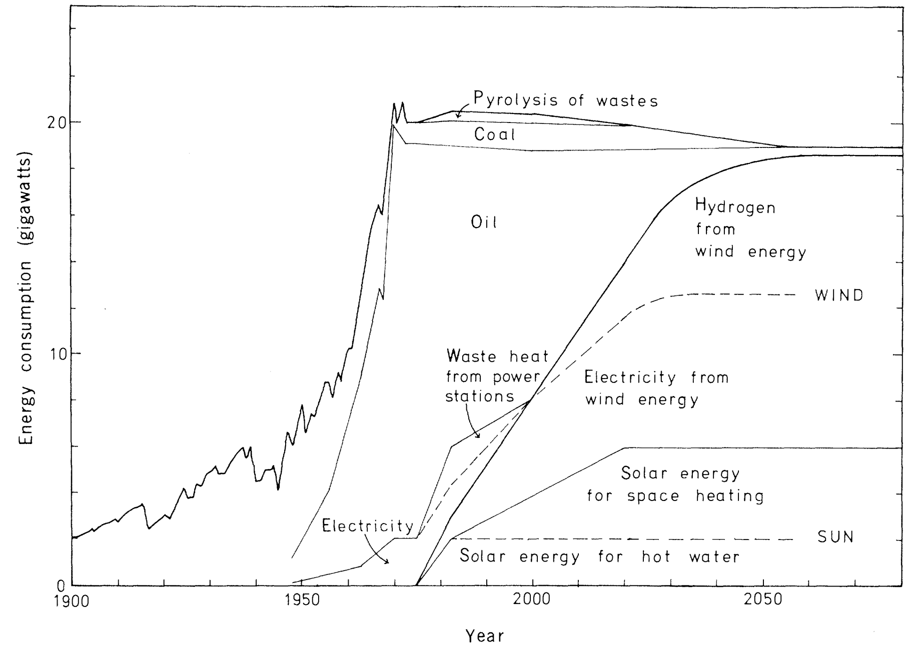

Fig. 4. Net energy consumption in Denmark, shown according to sources. Up to 1974, actual data are shown (*14*); data after 1974 indicate the proposed plan. The relative weighting between solar and wind energy shares might be altered, for example, if a major breakthrough occurred in the development of solar cells, making them competitive to wind-produced electricity under Danish conditions. The heavy, solid line indicates the proposed total share of solar and wind energy.

The rapid development of advanced telecommunication systems is expected to have considerable impact on all aspects of society and, in relation to energy consumption, particularly on the structure of business, commerce, and transportation. Advanced telecommunication systems are characterized by low energy consumption, and substantial energy savings can be expected when business meetings (all gatherings in which direct human contact is not essential) are based on videotelephone communication rather than on face-to-face communication requiring air and ground travel. Similar savings can be expected when trade on all levels, including shopping by individuals, is based on selecting merchandise from computerized video displays, so that actual transport of goods from place to place can be minimized (by computer), in contrast to the confusion of present-day private car traffic to and from supermarkets and inconveniently located shopping centers. In addition, many jobs could be handled from the homes of employees so that unnecessary commuter traffic could be avoided. On this basis a slight decrease in energy consumption in the transportation sector from 3.3 to 3.0 gigawatts in the year 2050 would seem to constitute an upper limit which would only be reached if the efficiency of energy conversion in the transportation sector were to drop from the present value of about 25 percent. This should not be unexpected if there has to be a conversion (for example, from wind energy) through hydrogen or other synthetic fuels.

The energy requirement in the agriculture and food industry sector is assumed to remain fairly constant at an average of 1.7 gigawatts.

In addition to the energy used for heating, households and commerce today use 1.3 gigawatts for cooking, light, and other electric equipment. This is assumed to rise slightly to 1.5 gigawatts, with a decreasing share going to commerce, because of the more efficient trade pattern mentioned above and the emphasis on producing goods with longer lifetimes and of higher quality, which generally will diminish the need for commerce. A large increase in the number of commodities installed in homes is expected to be partly compensated by the development of more energy-efficient equipment.

Due to increasing costs of raw materials, a substantial increase in recycling is expected to occur. In the year 2050 it is assumed that the recycling industry will use as much energy as is used today by all industries put together (3.7 gigawatts). I also assume that the production industry will, at the same time, have reduced its energy consumption slightly, to 3.1 gigawatts (partly by increased effectiveness and partly by reduced production of superfluous products). The improvements in building insulation that I propose, as well as the establishment of a new energy production system based on solar and wind energy, would require a rapid expansion of the corresponding industries. Not until the end of the 75-year transition period would these new industries have accomplished their task and would then gradually have decreased in size toward the proportions necessary for adequate maintenance of the energy systems; that is, the industries responsible for the repairs and replacements necessary for the energy systems and the buildings associated with them will reach a stage of equilibrium after 75 years of operation. The plan I propose for energy consumption after the year 1974 is summarized in Fig. 3.

Choice of Energy Systems

In deciding the amounts of energy that should be obtained from the different sources, I took into consideration the need to reduce Denmark's dependence on nonrenewable sources (oil in particular) as quickly as possible, and the desirability of basing as large a fraction of the energy consumption as possible on continuous (renewable) sources. My plan is outlined in Fig. 4. First, solar energy systems are utilized for hot water production. Such systems can be installed in existing buildings, the collectors being placed on the roofs or south-facing walls of the buildings, for example. The use of solar energy for space heating is expected to be introduced more slowly, because new buildings or substantial improvements in insulation will be required. Windmill-based heating could be an alternative during this period. Electricity-producing windmills are first to be placed at the west coast and in other wind-favored locations. As their capacity increases, and the present coal- and oil-based production systems become obsolete, storage systems will have to be added. Electrification is assumed to increase steadily, from the present 10 percent share of the total net energy consumption to about 33 percent in the year 2030. From about the year 2000, the storage systems such as those based on compressed air are expected to become insufficient and a hydrogen-based economy will be introduced, so that by the year 2050 close to the entire energy requirement (including that of transportation) may be obtained by conversion of sun and wind energy. Various types of batteries might take the place of hydrogen as a storage medium.

During the transition phase the desired decline in oil importation could be assisted by short-term solutions, such as the utilization of waste heat from conventional power plants (for local heating) and the pyrolysis of wastes, which may contribute about 0.8 gigawatt [10 gigajoule per ton of waste (*13*)]. As the recycling of used goods increases, the energy content of the wastes will decrease, and this energy source will become negligible.

Summary

Two possible futures for the industrial world may be distinguished: (i) Large amounts of low-cost energy become available and the more energy-intensive methods for extracting resources from lower-grade deposits continue to sustain industrial expansion until either the environmental impact becomes unacceptable or ultimate limits, such as climate disruptions, put an end to such growth. (ii) The cost of nonrenewable energy resources continue to rise, but a fixed amount of energy from continuous sources may be utilized at constant cost. In this case a lower production level may be set by the amount of energy that is available from renewable sources, and society may thus have to be reshaped with energy economization in focus. If it is possible to choose between these two alternatives, the choice should be based on a discussion of the pros and cons of each one, and in particular on the desirability of having to process an increasing fraction of the earth's crust in search of raw materials in order to maintain growth as long as possible. However, the availability of the first option is far from certain and it thus seems reasonable to plan for the second alternative.

I have tried to propose such a plan for a small, homogeneous geographical region, namely Denmark. The ceiling on the consumption of energy from continuous sources is chosen in accordance with the criterion of not having to convert a major part of the land area to energy-collecting systems. The proposed annual average energy consumption of 19 gigawatts by the year 2050 corresponds to solar energy collecting panels (in use only 50 percent of the time) with an area of roughly 180 square kilometers and a windmill swept area of about 150 square kilometers. These (vertical) areas constitute less than 1 percent of the total land area.

The selection of solar or wind energy for different applications has been based on known technology and may be subject to adjustments. The project has been shown to be economically feasible according to estimates of the cost of various alternatives during the 25-year depreciation period adopted. However, the initial cost per energy unit produced is higher than that for most of the alternatives, so that action is not expected to be taken immediately as a result of purely private initiative. In a public economic evaluation, other factors must be considered in addition to the cost of energy per kilowatt-hour. At present, Denmark has over 10 percent of its labor force out of employment and a substantial deficit on its balance of payments, so that an early start on the solar and wind energy project, based on national industry, would have additional payoffs compared with energy systems based on imported technology or imported fuels. Several factories that are now being closed down as a result of the economic crisis could be adapted to the production of parts for solar or wind power systems, and the building industry, badly hit by unemployment, would receive legitimate work.

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