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CENTRAL PLACE THEORY AND THE KEY TO HYDROGEN DOMINANCE *

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ABSTRACT

Central-place theory plays a crucial role in interpreting the spatial organization of human activities. Simply, it states that there is a breakeven between the advantages of concentrating more and more production and processing in one area and the costs of spreading the products further and further away. The balance between these gains and costs fixes the sizes of production units and their market areas, which finally appear as a roughly hexagonal checker board.

A critical parameter is the "transportability" of the product. Low transportation costs favor large production units and large captive areas. Hydrogen, with its low transportation costs, as a gas or as a liquid (LH_2), is ideally suited as an energy vector for very large nuclear or fusion primary energy generators.

KEYWORDS

Central-place theory; energy carriers (hydrogen and electricity); energy transportation costs; spacial energy density; economies of scale; pipelines.

GENERAL THEORY

Central-place theory rationalizes a compromise between production and transportation costs people have always reached by trial and error. Peasants carry their goods to a weekly market if they can travel there and back in one day. Subtracting marketing hours leaves a couple of hours walking time both ways, so these markets draw people and goods from a distance of about 10 to 15 km, as has been shown experimentally. The situation is perfectly analogous for a bakery, an oil refinery, or an ammonia plant. That the area to which they are linked cannot exceed certain limits defines the size of the plant (Fig. 1).

Thus, saying that large is economical has to be taken with a pinch of salt. For every situation there is an optimal size, and only areas with low-level consumption can find small sizes optimal.

They key element in the very simple mathematics is the economy of scale in manufacturing, usually expressed as

$$C = a\,S^{b} \quad ,$$

where C is the cost of the product, S the size of the plant, and a and b are constant. If $b < 1$ there is a continuous advantage in increasing size. Analysis of case histories shows that when a system demands large sizes, technology and industry always find a way to provide the appropriate equipment.

For chemical plants b is often 2/3, whereas for large oil tankers it can be 0.4. These figures are only indicative, as they may change under different circumstances and usually fail at the top end of the scale, because the appropriate technology is still immature when the system is still growing. Using literature pre-dating the great commotion about nuclear energy I found consistently b values of around 0.45 for nuclear reators. This powerful economy of scale is

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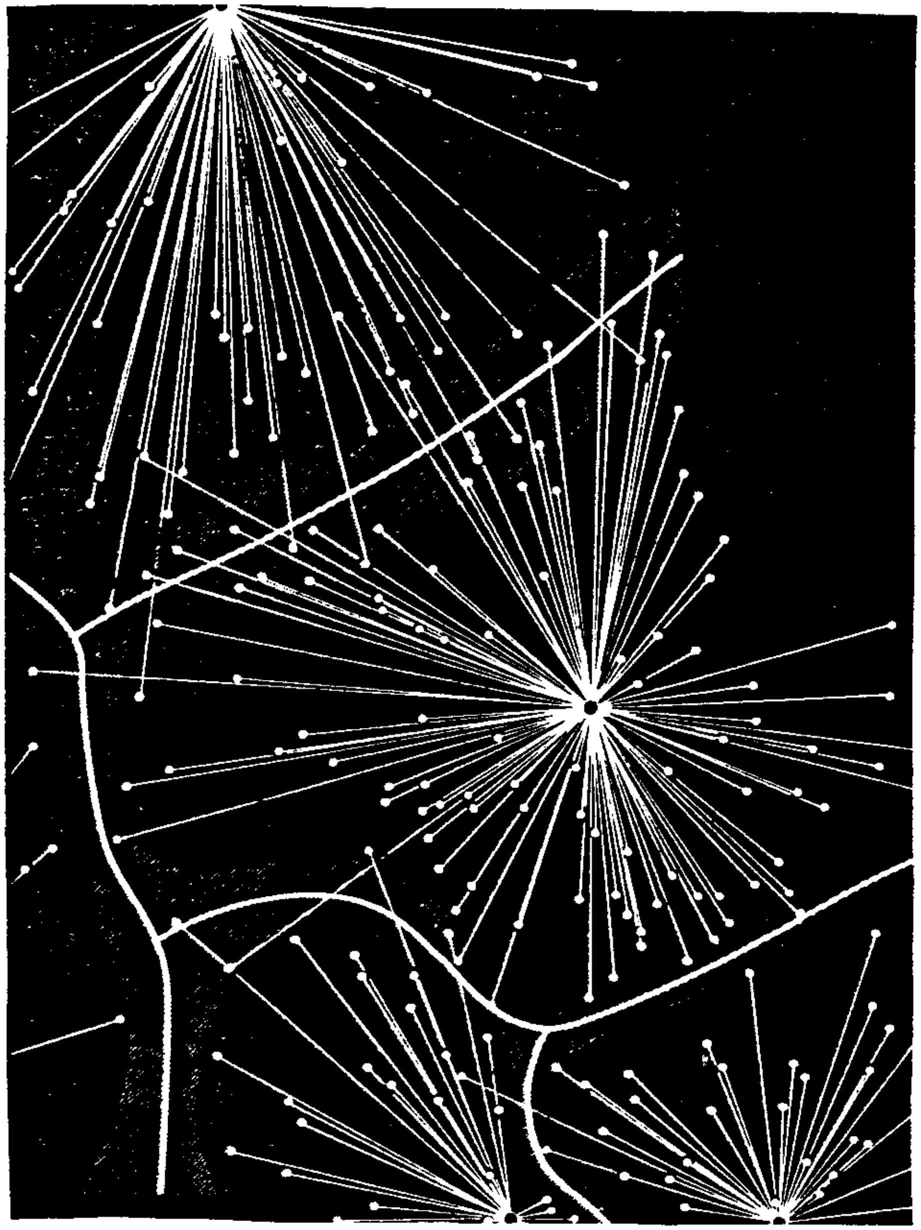

Fig. 1

understandable since the core volume grows in proportion to the power, but many other factors, such as control, buildings, and land, stay basically the same.

The counterpart to production economics is the cost of transporting the product, which also has economies of scale. A large pipe carries gas more economically than a small one, such that, approximately, the transportation cost is inversely proportional to the diameter of the pipe. But the amount carried is dependent on the cubic power of the diameter, so to obtain an economy of scale requires large changes in the volumes transported.

Transportation costs are often quite stiff, especially where the product is carried in separate units, as with truckloads, rail cars, or barges. In such cases the size of the plants is basically sensitive only to the spatial intensity of the market. This occurs in the U.S., as shown in Figs. 2 and 3 where the size of ammonia and ethylene plants are given together with the size of the market during the last 30 years.

I first used this kind of analysis about ten years ago when trying to find the underlying reasons for Western countries changing their primary energy source from wood to coal to oil to gas. Of the innumerable factors that may affect this change, the strongest appears to be linked to economies of scale in the exploitation and transportation of primary energy sources.

Sources with large economies of scale are preferable when the scale becomes larger, i.e., when the market grows. So the independent variable in the evolution of the system becomes spatial changes in intensity of energy consumption and not calendar time, i.e., technological development. Natural gas was used in China 1000 years ago, in special cases, and also rotary drilling, but the technique made economic sense only for a large city (Beijing) with gas fields nearby. During the last 30 years, on the one hand, total energy consumption has increased greatly, on the other, the population has departed from the land and concentrated in cities. This created an essential prerequisite for the development of natural gas grids and of its increasing consumption. In other words, the economies of scale of transporting natural gas make it the number one candidate for providing the energy of the future. How different primary fuels strive globally for their share of the markets is shown in Fig. 4.

A special case of an energy infrastructure is provided by the electricity system. There was much discussion in the late 1970s about which size nuclear power stations were best. The arguments were very mixed, but the above renders the problem clear: the question has no meaning out of context. The optimal size of the generating station is determined by the spatial intensity of consumption (kW/km^2) and has relatively little to do with the technical capacity to build larger and hopefully cheaper nuclear power stations.

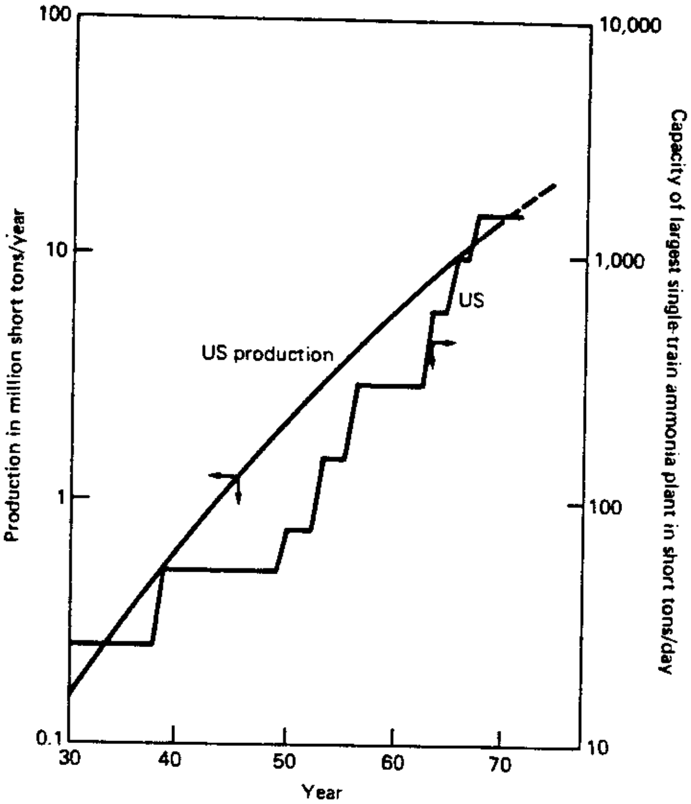

Fig. 2. Relation between largest plant size and production in the U.S., ammonia.

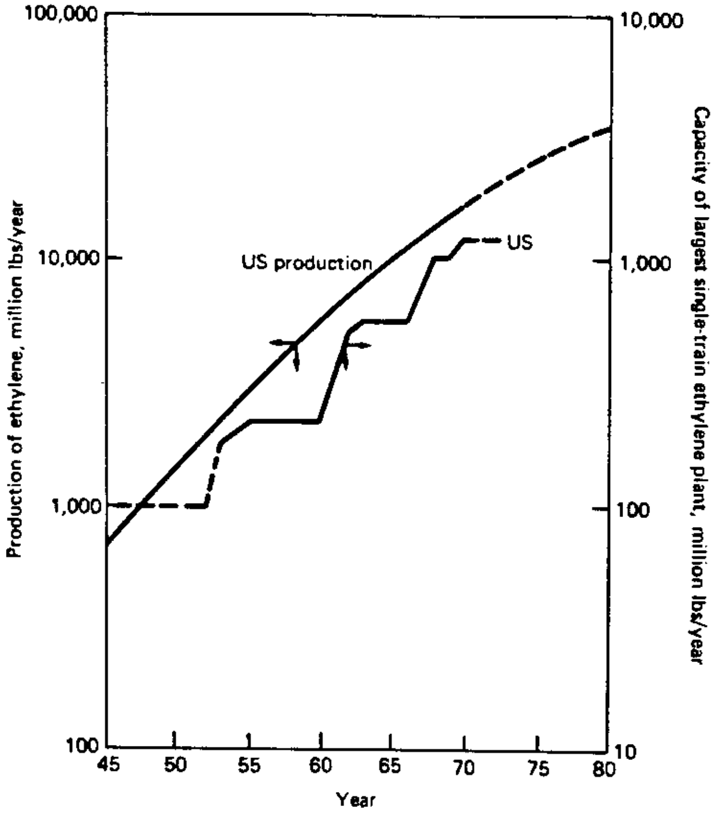

Fig. 3. Relation between largest plant size and production in the U.S., ethylene.

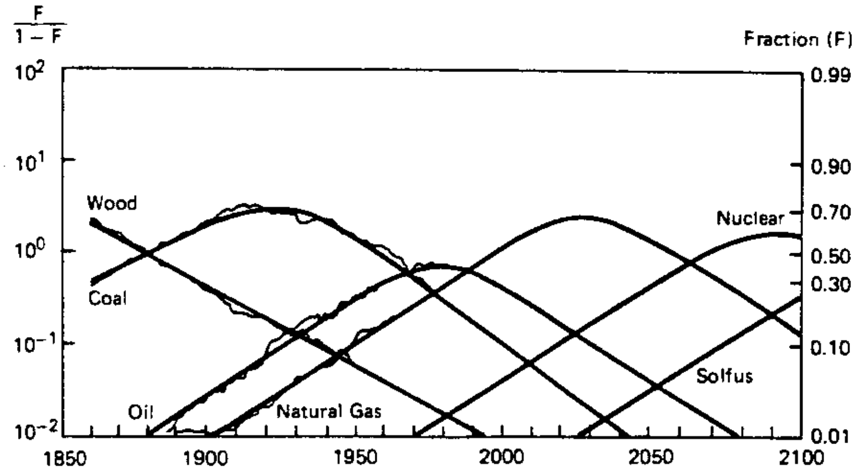

Fig. 4. World primary energy substitution. Source: N. Nakicenovic (1984).

In order to verify this statement experimentally, I examined the statistics for consumption of electrical energy in the U.S. and the size of electricity generators since 1900. Electricity consumption increased quite regularly, doubling every seven years. There were naturally oscillations in the rate, depending on booms or recessions, but the trend was maintained in the long run. Generator size actually did double every six years, from the "jumbo" dynamos of Edison with a power of about 10 kW to present generators with powers of 10^6 kW. Every time engineers developed generators too large for their time, one or two were built and that was it. Incidentally, one of the curious consequences is that the total number of generators keeps decreasing!

HYDROGEN AS AN ENERGY CARRIER

As Fig. 4 shows nuclear power will keep growing during the next 100 years, so the network through which nuclear-generated energy will be distributed is obviously of paramount importance in defining the future features of the system. These features will depend on the characteristics of the medium used to transport energy, be it electricity, hydrogen, hot water, or whatever. So I compared the characteristics of possible candidates (Table 1), in particular their transportability. The figures are only indicative, since often the cost of transport depends on the amount transported, but their inevitable imprecision does not mask the enormous differences: hot water will never be better than methane.

TABLE 1. Energy Transportability and Generation Size

	Transportability (km)	Technical Maximum (km)	Size of Generation (GW)
Hot water	~2	50	0.2
Electricity	100	1000	1
H_2	1000	3000	100
Compressed air	2-3	10	10^{-3}
Adam/Eva	20	200	.04
Natural gas	1000	3000	100
Oil	10^4	10^4	2000*

*Possible production from a field.

The possible competitors for transporting nuclear energy from the nuclear plant are really only electricity and hydrogen. Electricity is certainly a marvelous energy vector, clean, fast, and easily controllable. It has also the great advantage of being already here. But it also has a serious disadvantage: it cannot be stored. This means the production and transportation systems are determined by the maximum demand over the year. But we have days and nights, and summer and winter to modulate the activity of people, and the mean demand equals only half the peak demand. This means all our beautiful equipment works, on the average, at only half capacity. But one of the basic principles of efficient enterprises is that even when you sleep, your capital must work for you. In an energy system such as the electrical one, where all is capital, this utilization factor of 50% is a really serious problem.

The second drawback due to nonstorability is that dispersed consumption, as for vehicles, is difficult to access. Certainly, many new developments will occur in the next waves of innovation, e.g., star-war technology may make airplanes fed by laser beams a feasible prospect, but as these developments are very long term, they are not relevant here.

The third drawback is that transporting electrical energy is quite expensive and this is actually why the kWh (transported over distances) is equivalent, on average, to 100 km. Natural gas, on the contrary, is now transported over an equivalent mean distance of 1000 km.

Hydrogen is transported in pipelines much like natural gas, i.e., with similar economies. On the other hand, in industrialized countries nonelectrical energy demand, as seen from the consumer end, is now about an order of magnitude larger than electrical energy demand. Even assuming further penetration of electricity the ratio will probably stay in this order of magnitude. Thus, if hydrogen becomes the energy vector, it will have economic distances comparable to those for natural gas, i.e., about 1000 km plus. If we could construct a nuclear-plus-hydrogen system in the U.S. to satisfy nonelectrical energy demand, the optimal size of the nuclear plants producing this hydrogen would be 100 times ($1000^2/100^2$) those producing electricity today with all the economies of scale these very large sizes promise. Because 1000 km is quite a distance, every continent could have optimally a dozen or so hydrogen-generating centers (holy towns of energy) so that not only would the economies be optimized, but also the technological levels of operation and safety.

In summary, from an intrinsic point of view hydrogen is highly advantageous as an energy vector. Its extreme flexibility makes it a choice fuel for all the uses in which fossil fuels are now employed and consequently the substitution could be complete. Its storability, especially in underground porous structures, as natural gas is now stored, would make its production independent of demand, so maximizing plant utilization. Its transportability would make it perfectly compatible with a system in which scale is at a premium: for nuclear reactors or better fusion reactors.

As I explicate in a paper on the development of nuclear energy (Marchetti, 1985), the critical years for the start of this new technology are the next twenty. Its destiny is thus in the hands of our generation.

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