WORKING PAPER

CENTRAL PLACE THEORY AND THE DOMINANCE OF HYDROGEN AS AN ENERGY CARRIER

C. Marchetti

October 1985
WP-85-73

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INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS
A-2361 Laxenburg, Austria

RESUME

Central place theory plays a central role in interpreting the spacial organization of human activities.

Simply stated it says there is a breakeven between the advantage of concentrating more and more production and processing and the cost of spreading the products further and further away.

The balance between these gains and costs fixes the size of the production units and of their market areas which finally appear as a roughly exagonal checquer board.

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

CENTRAL PLACE THEORY AND THE DOMINANCE OF HYDROGEN AS AN ENERGY CARRIER

Central place theory rationalizes things people have done since ever. Peasants carry their goods to a weekly market if they can go there and come back in one day. Take away marketing hours, and you'll have a couple of hours walking time. These markets draw in fact people and goods from a distance of about ten to fifteen kilometers, as it is experimentally known.

The situation is perfectly analogous for a bakery, an oil refinery, or an ammonia plant. The fact the area to which they are linked cannot exceed certain limits, also defines the size of the plant.

The say that large is economical has to be taken with a grain of salt. For every situation there is an optimal size. Areas with low level consumption usually find as optimal small sizes.

The key elements in an altogether simple mathematics are the economy of scale in manufacturing usually expressed in the form:

$C = a\ S^b$ where C is the cost of the product, S the size of the plant, and a, b are constants. If $b < 1$ there is a continuous advantage in going big. We see in fact experimentally, that when there is a system demand for large sizes, technology and industry always find a way to provide the appropriate equipment.

The key parameter in expressing the advantage of going big is b. For chemical plants b is often 2/3. For large oil tankers it can be equal to .4. These figures are only indicative as they may change under many circumstances and usually fail at the top of the sizes, because technology there is still immature when the system is dynamic. Using literature before the big fuss about nuclear energy I found consistently for nuclear reactors b values around .45. This powerful economy of scale is understandable if one thinks that the core volume grows in proportion of the power, but many other things like control, buildings, and land stay basically the same.

The counterpart in production economics is the cost of transporting away the product. Also this has economies of scale. A larger pipe carries gas more economically than a small one. In very round figures, the transportation cost is inversely proportional to the diameter of the pipe. But the amount carried is near to the cube power of the diameter, so to get an economy one has to go to great changes in volumes transported.

Transportation costs are in fact quite stiff, especially in the case where the product is carried in lumps like truckloads, railway cars or barges. This means the size of the plants is basically sensitive only to the spacial intensity of the market. This is shown experimentally in the case of US, where the size of ammonia and ethylene plants is given together with the size of the market during the last thirty years.

I entered into that kind of analysis about ten years ago when trying to find the deep reasons for Western countries to move from wood to coal to oil to gas. Out of the innumerable factors that may enter the picture, the strongest ones appear to be linked to the economies of scale in the exploitation and transportation of the primary sources.

Sources with high economies of scale get their chances when the scale becomes larger, i.e., when the market grows. So the independent variable in the evolution of the system becomes spacial energy intensity of consumption, and not time, i.e., technological development. Natural gas was used in China thousand years ago, in special cases, and also rotary drilling, but the technique made sense only for a large city (Beijing) with gas deposits nearby. During the last thirty years on one side total energy consumption greatly increased, on the other population left the land imploding into the cities. This has created an excellent prerequisite for the development of natural gas grids and consumption. In other words, the economies of scale for transporting fuel gas make a gas the candidate number one for providing the energy grid of the humanity of the future. How different primary fuels strive for their share of the markets is reported in Fig. 3.

A special case of energy infrastructure is provided by the electric system. There has been much discussion at the end of the seventies avout what size nuclear power stations should have. The arguments were very mixed, but after what I said the problem becomes clear: the question has no meaning out of context. The optimal size of the generating station is determined by the spacial intensity of consumption (kw/km^2) and has relatively little to do with the technical capacity of building larger and hopefully cheaper nuclear power stations.

In order to verify this statement experimentally, I did look into the statistics of consumption of electrical energy in US, and the size of electric generators since 1900. Electric consumption quite regularly grew, doubling every seven years. There were naturally oscillations in the rate, depending on booms or recessions, but the trend was kept well in the long run. The voltage in the high power lines doubled every 22 years, meaning roughly a doubling of the "market" seen by a power plant, which is today about one hundred km radius.

By combining the two one could calculate a doubling of the size of generators every six years, if the central market rules are respected. Generators actually doubled every six years, going from the "jumbo" dynamos of Edison with a power of about 10 kw to present generators with powers of 10^6 kw. Every time clever engineers came in with generators too large for their time, one or two were built and that was it.

One of the curious consequences is that the number of generators keeps always decreasing!

It is now time to converge on the hydrogen question. As Fig. 3 shows nuclear will move to dominance during the next hundred years, and the network through which nuclear generated energy will be distributed is obviously of paramount importance in defining the features the system will take. These features will depend on the characteristics of the medium used to transport the energy, be it electricity or hydrogen or hot water, or what else. So I brought the possible candidates together in Fig. 4, to compare their characteristics, in particular their transportability. The figures are only indicative as often the economy of transport depends on the amount transported, but their inevitable imprecision does not mask the enormous differences, that water will never beat methane so to speak.

The two possible competitors for transporting nuclear energy out of the nuclear plant are really electricity and hydrogen. Electricity is certainly a marvelous energy vector, clean, fast, and easily controllable. It has also the great advantage of being already there. But it also has a serious disadvantage: it cannot be stored. This means the production and transportation system have to be sized on the basis of the maximum demand over the year. But we have days and nights, and summer and winter to modulate the activity of people, and finally mean demand equals one half peak demand. This means all our beautiful equipment works in the mean only half time. 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 like the electrical one, where all is capital, this problem of an utilization factor of 50% is a really serious one.

The second drawback coming from the non-storability is that dispersed consumption like for vehicles is of difficult access for an electrical system. Certainly many new things will come in the next wave of innovations, and star war technology may make airplanes fed with laser beams a feasible prospect, but as these new things take very long times to diffuse, let's keep them for the really long range.

The third drawback, waiting for room temperature superconductors, is that transporting electrical energy is quite expensive. This is why the kwh travels in the mean about one hundred kilometers.

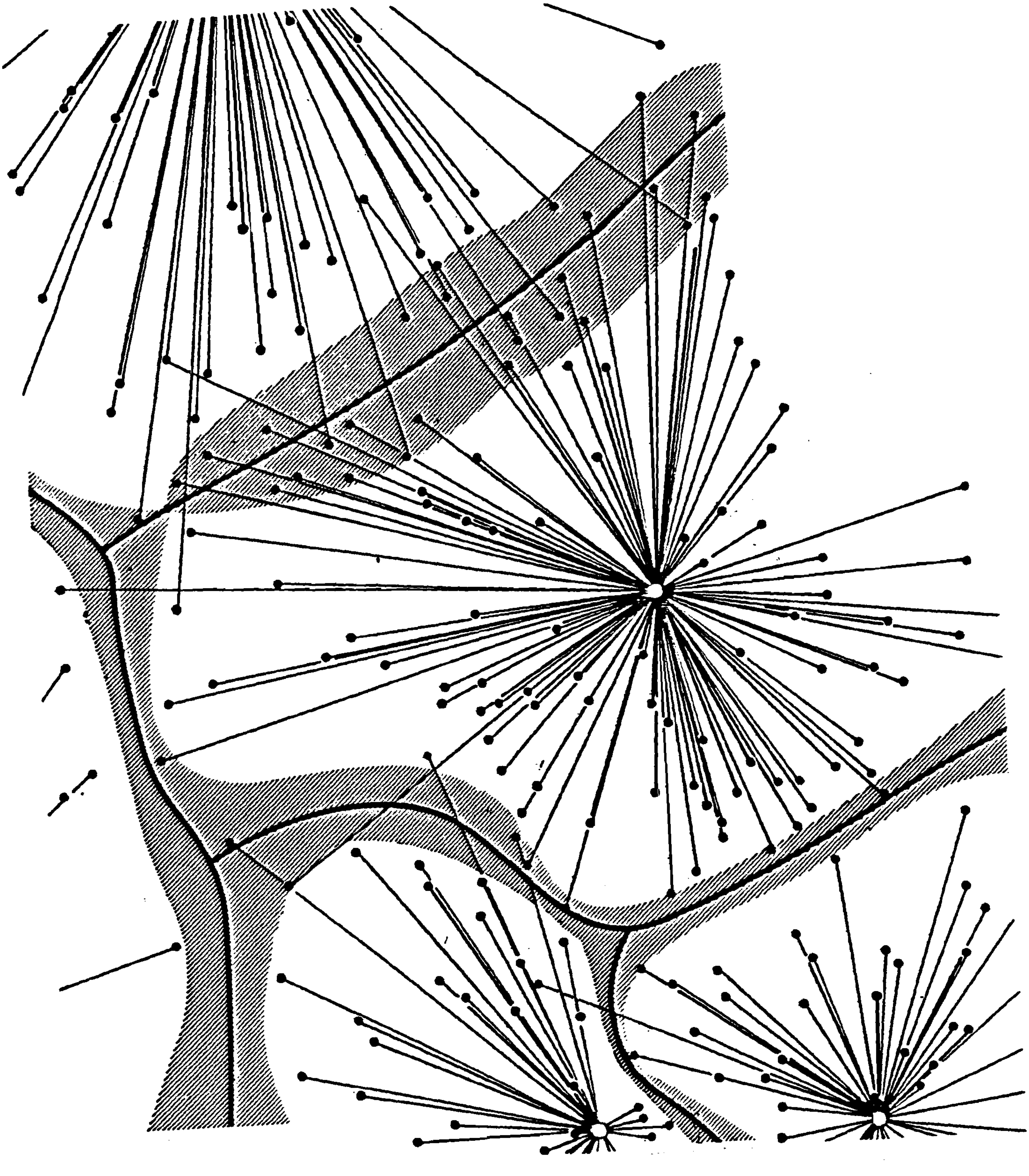
Hydrogen transports in pipelines much like natural gas, i.e., with similar economies. On the other side non-electric energy demand, as seen from the consumer end, is now about an order of magnitude larger than electric energy demand, in industrialized countries. Even assuming further penetration of electricity the ratio will probably stay in the order of magnitude range. This means if hydrogen will become the energy vector, it will have economic distances comparable to those for natural gas, i.e., in the range of the 1000 km plus. If by magic we could construct a nuclear plus hydrogen system in the US to satisfy non-electric energy demand, the optimal size of the nuclear plants to produce this hydrogen would be 100 times ($1000^2/100^2$) the ones to produce electricity today. Because 1000 km is quite a distance, every continent could have *optimally* a dozen or so hydrogen generating centers, kind of holy towns of energy where not only economy would be optimized, but technological levels of the operations and safety.

I think at this point I can wind up my arguments as the main logic has been already deployed.

From an intrinsic point of view hydrogen is highly advantageous as an energy vector. Its extreme *flexibility* make it a choice fuel for all the uses where fossil fuels are now employed. Its *storability*, especially in underground porous structures, the same way natural gas is now stored, would make its production independent of demand, so optimizing the utilization factor of the plants.

Its *transportability* would make it perfectly matched to a system where scale is at a premium, as for nuclear reactors or better fusion reactors.

As I explicated in a paper to come out soon in our journal, the critical years for the start of this new technology are the next twenty. Its destiny is in the hands of *our* generation.

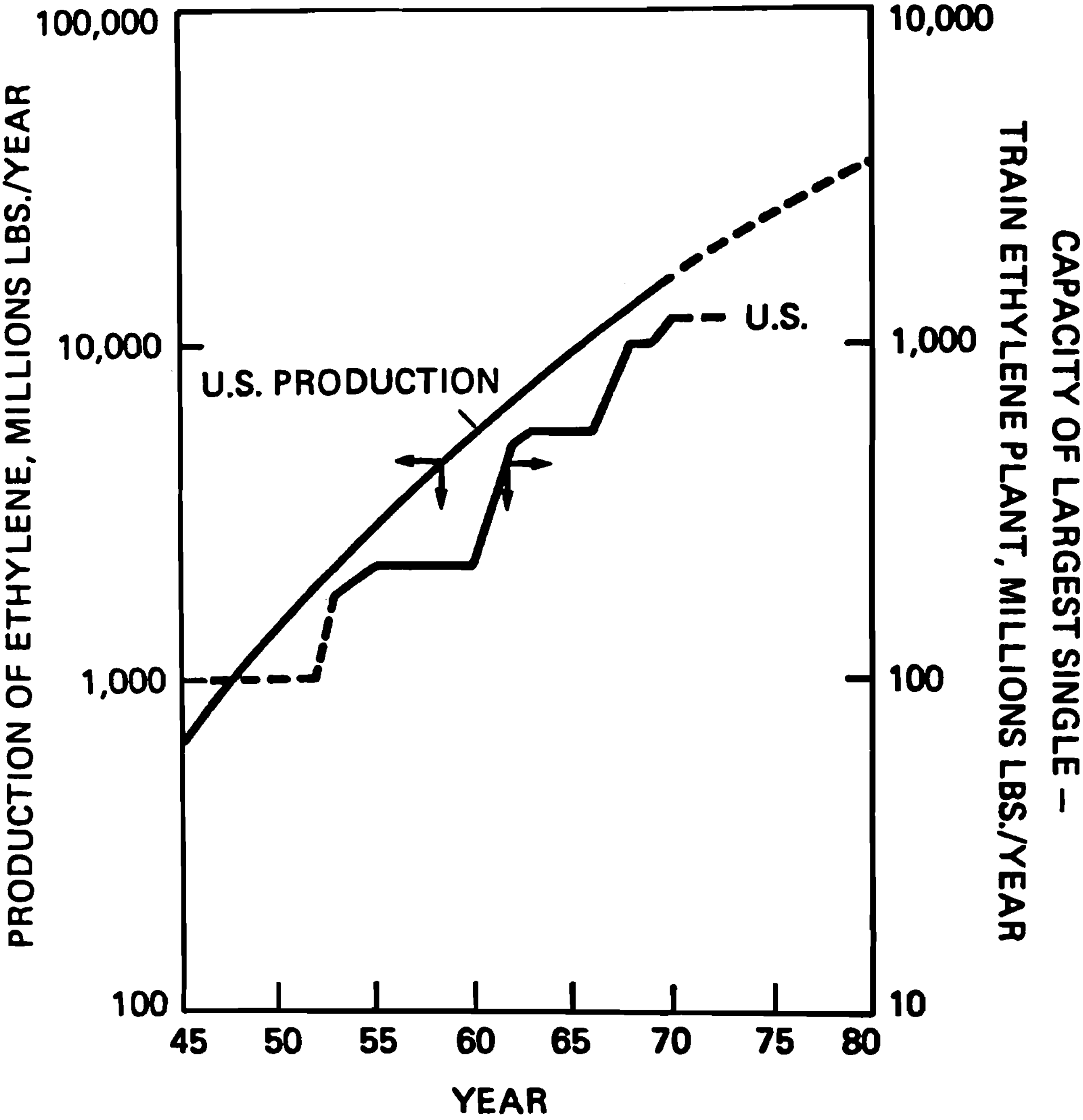


ENERGY TRANSPORTABILITY & GENERATION SIZE

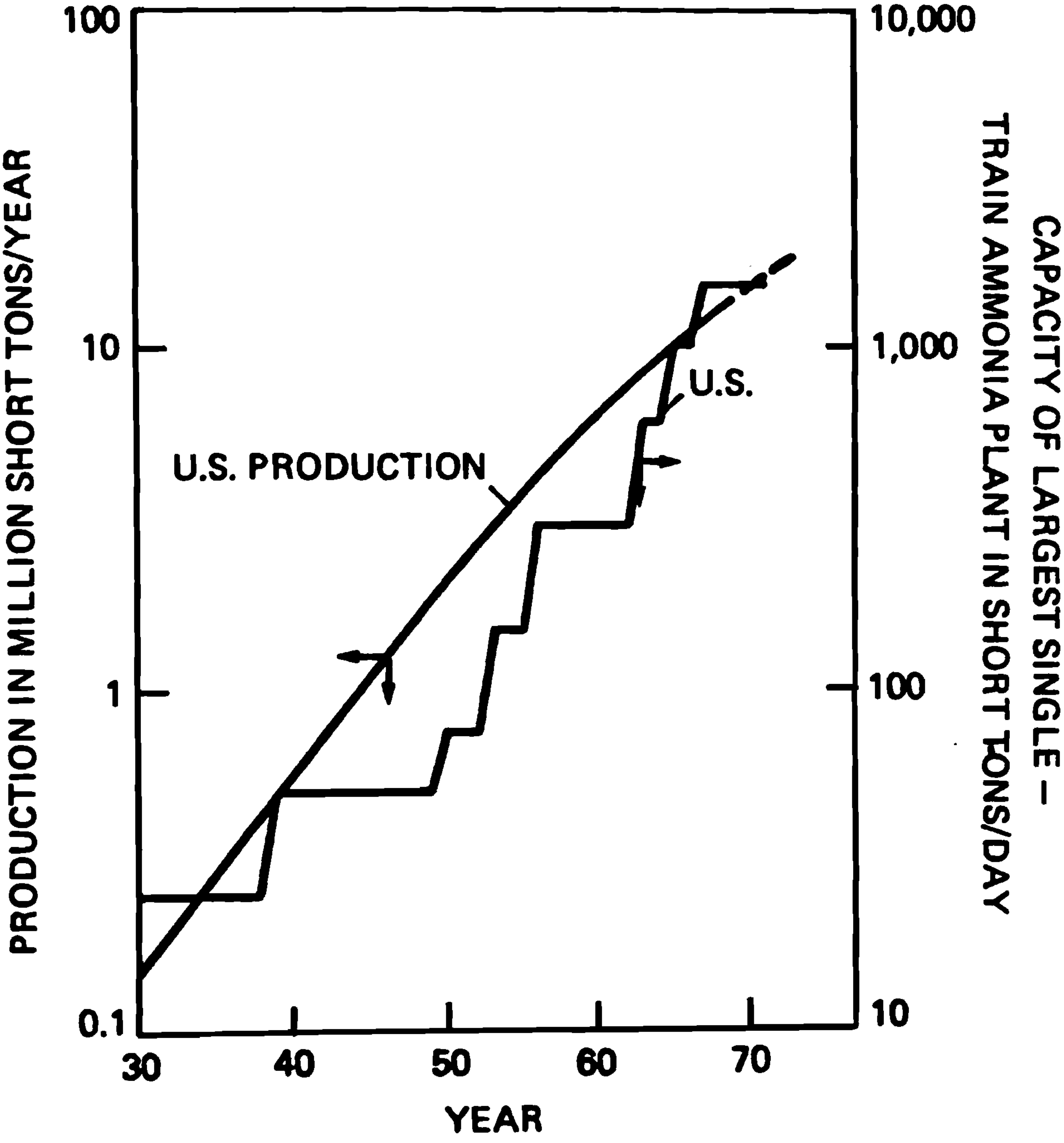
	TRANSPORTABILITY [km]	TECH. MAX. [km]	SIZE OF GENERATION [GW]
HOT WATER	~2	50	0.2
ELEC.	100	1000	1
H_2	1000	3000	100
COMP. AIR	2 – 3	10	10^{-3}
ADAM / EVA	20	200	.04
N.GAS	1000	3000	100
OIL	10^4	10^4	2000 x)

x) POSSIBLE PRODUCTION FROM A FIELD

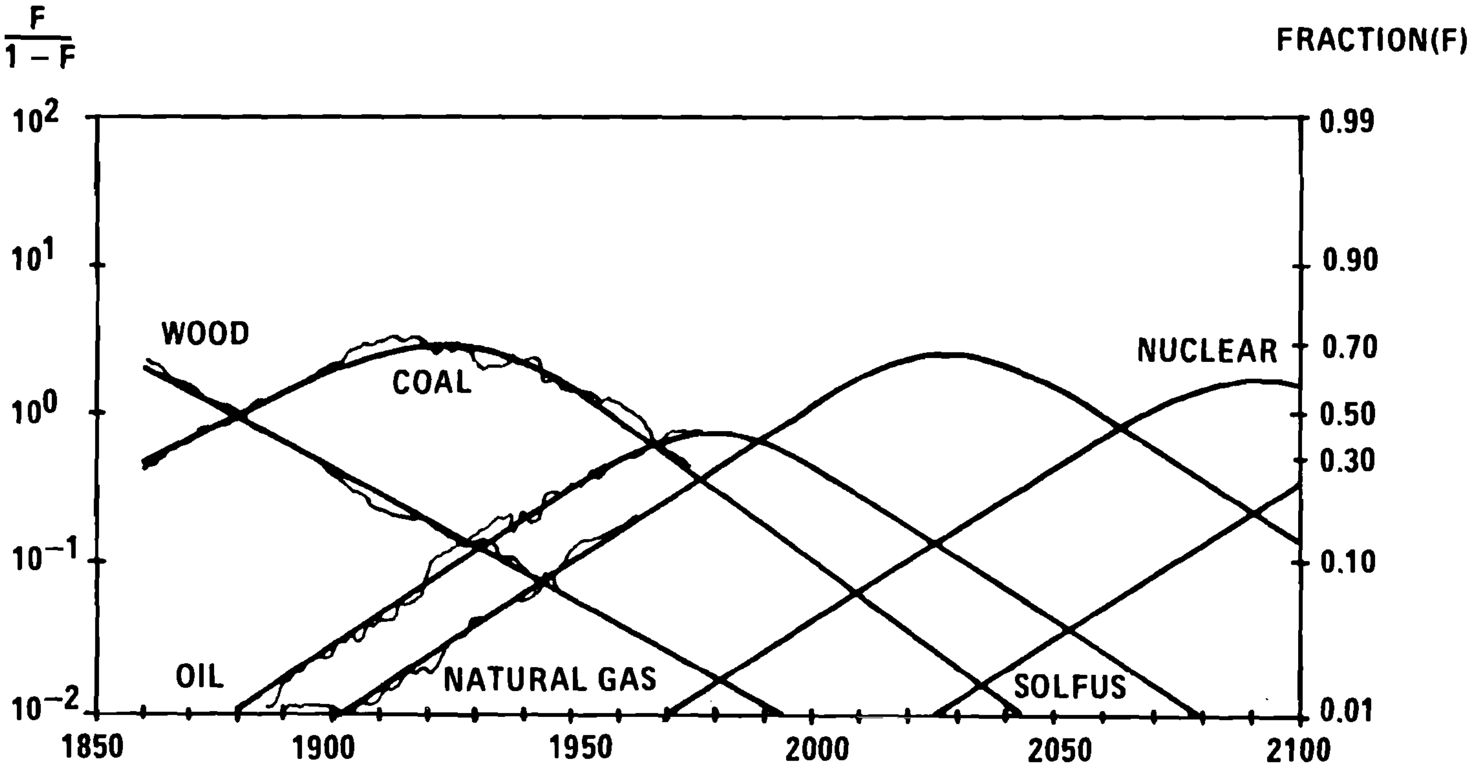
RELATION BETWEEN LARGEST PLANT SIZE AND PRODUCTION IN THE UNITED STATES – ETHYLENE



RELATION BETWEEN LARGEST PLANT SIZE AND PRODUCTION IN THE UNITED STATES – AMMONIA



WORLD PRIMARY ENERGY SUBSTITUTION



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