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The Future of Natural Gas
A Darwinian Analysis*

CESARE MARCHETTI

ABSTRACT

Market substitution analysis has been a reliable tool for describing the dynamics of energy markets during the last 200 years. It is used here to project the evolution of the world energy system during the next 200 years. The exercise draws its interest from the extraordinary stability of socioeconomic processes, which becomes manifest when appropriate parameters are chosen to measure them and a Darwinian conceptual frame is used to organize them. We have worked out a thousand cases. In order to read the startling results correctly, one should remember Edison christened his 10-kilowatt dynamo "Jumbo." Our energy system will grow beyond today's imagination requiring a rethinking of its structure to make it compatible with the context.

The future is in a large measure a deconvolution of the past with seeds of novelty carefully selected and planted by the system itself. This far-reaching statement is supported by a large body of evidence amassed at IIASA during the last ten years.

The first subject that we analyzed was primary energy at the world level, and natural gas was clearly well in the picture. Just ten years ago we declared its inevitable progress, which the press opposed, arguing that it should be saved for future generations, so limited were its supplies.

The consequences of that analysis were never fully explicitated. I will do so now, using a concept familiar to economists—the product life cycle. A primary energy is in fact a product, substituting for, and substituted by, other products, so the concept is fully applicable. I will also analyze coal and oil for comparison.

The original primary energy competition is reported in Figure 1 [4], as a more recent version with data up to 1982. For coal the penetration starts at a market share of about 30% (1860) so the previous share has to be reconstructed by logistic backcasting. Figures 2, 3, and 4 show coal, oil, and gas, respectively, in terms of life cycles, from an initial 1% of the world market to a final 1% of the market.

For coal the cycle spans 300 years, for oil 200, and for gas 250. These figures are not really related to size of the resources, but only to the timing of the introduction of the competitor. Oil was introduced somehow "late," according to the general rules of

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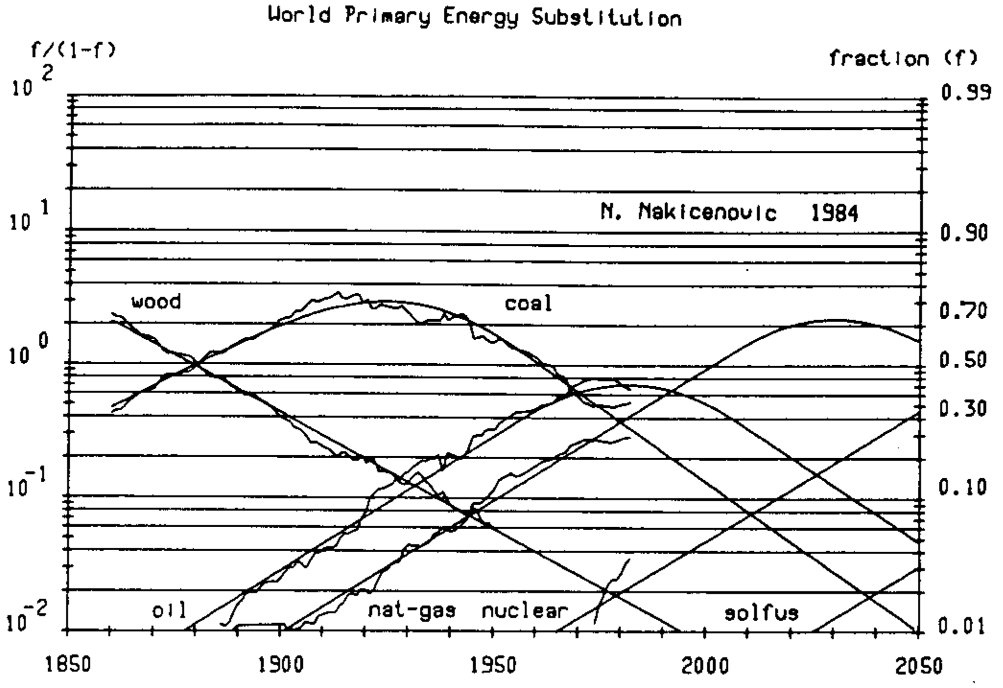

Fig. 1. The primary energy market substitution analysis, originally made in 1974, has been here adjusted with data to 1982. The lower than expected penetration of natural gas is a signal for fast growth in the near future. As the past shows, deviations are always reabsorbed elastically. Reported are market shares.

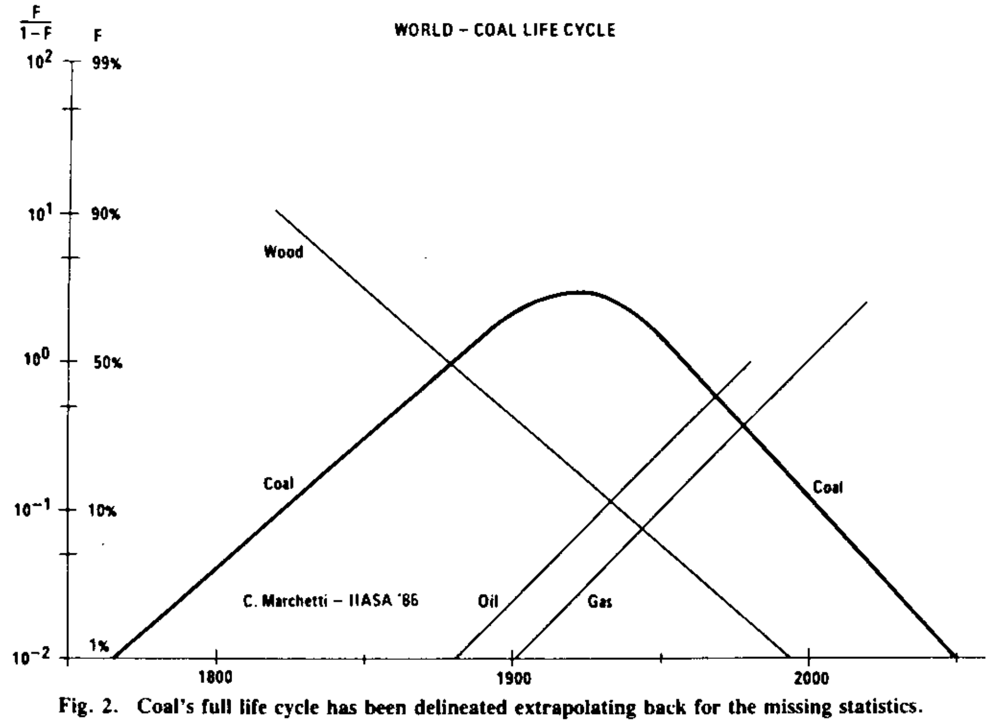

Fig. 2. Coal's full life cycle has been delineated extrapolating back for the missing statistics.

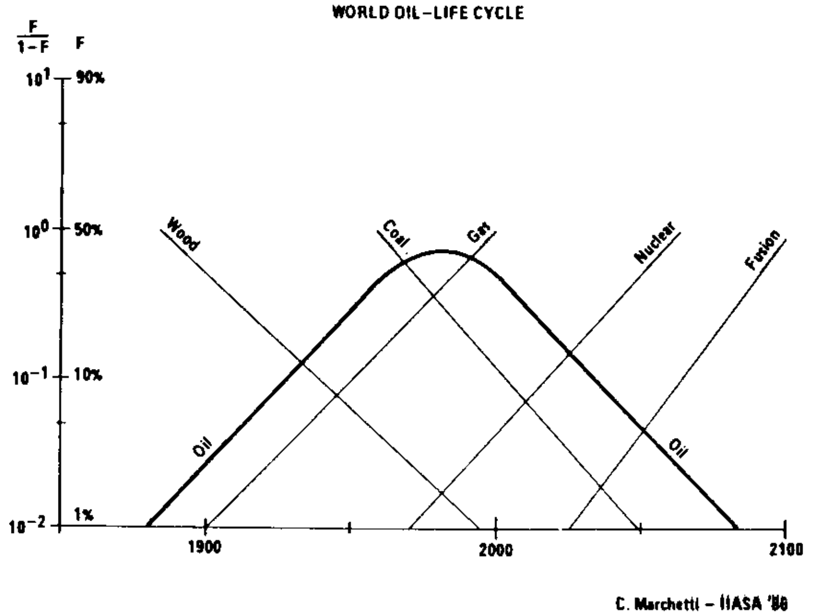

Fig. 3. Oil's full life cycle delineated. The shortness of the cycle is due to gas being introduced shortly after the introduction of oil.

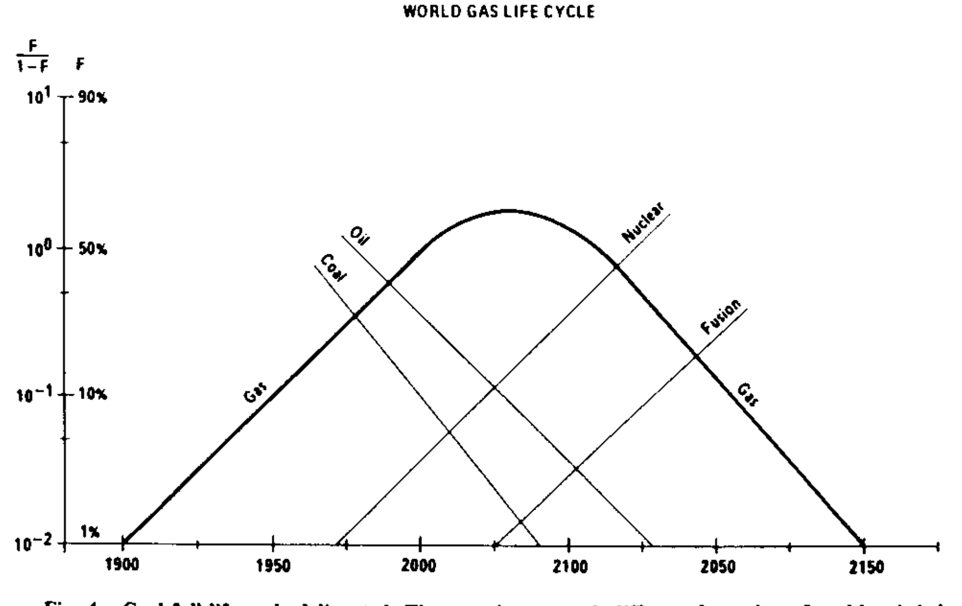

Fig. 4. Gas' full life cycle delineated. The span is not much different from that of coal but it is in a later phase of an exponentially expanding market so that absolute quantities will be very large in comparison.

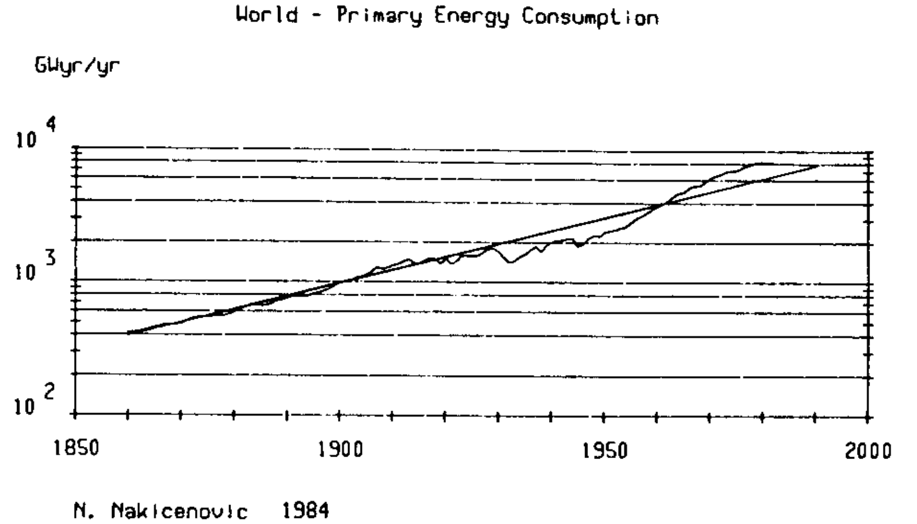

Fig. 5. Business-as-usual extrapolation of energy consumption at the secular growth rate of 2.3%. The oscillations are due to 55 year Kondratieff cycles.

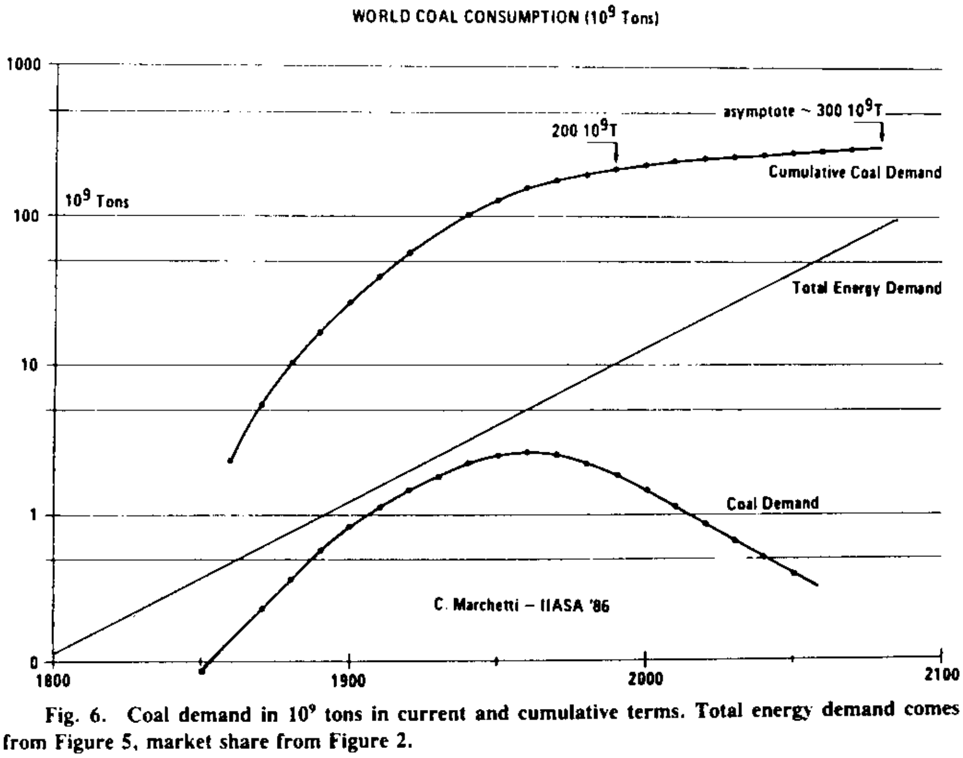

Fig. 6. Coal demand in 10^9 tons in current and cumulative terms. Total energy demand comes from Figure 5, market share from Figure 2.

innovation waves and new primary energies introduction [2]. For this reason coal has its broad time span and its high maximum market penetration of about 75%. Gas being timely, the loser is oil with its maximum penetration a little below 50%. Natural gas should go a little above a 70% market share in 2030. But as we will see, because the total market is growing in time, the total amounts extracted during the life cycle increase in the order: coal, oil, gas.

To go into absolute values, we may hypothesize that the world energy market is growing logistically. In the US, logisticity starts showing now with a per capita consumption of about 15 tce/year. It may be fair to assume the world with about 2 tce/year will stay exponential for a while. It has during the last century, with a growth rate of 2.3%/year (i.e., total consumption doubling every 30 years) (Figure 5). Our time span is 150 years ahead; assuming a doubling of world population every 70 years (at present rates of growth it would double in 35 years), we arrive at a per capita consumption at world level in the same ballpark as the US per capita consumption at *present*. Our hypothesis regarding total energy growth during the next 150 years is business as usual.

At this point I will show the results of the simple calculations that follow the hypothesis. In Figure 6 world coal consumption is given. It shows demand peaking around 1980 with 2.5×10^9 tons. Demand will still be about 0.4×10^9 tons in 2050. The decrease in consumption will be quite cushioned as it corresponds to a loss of about 2.5%

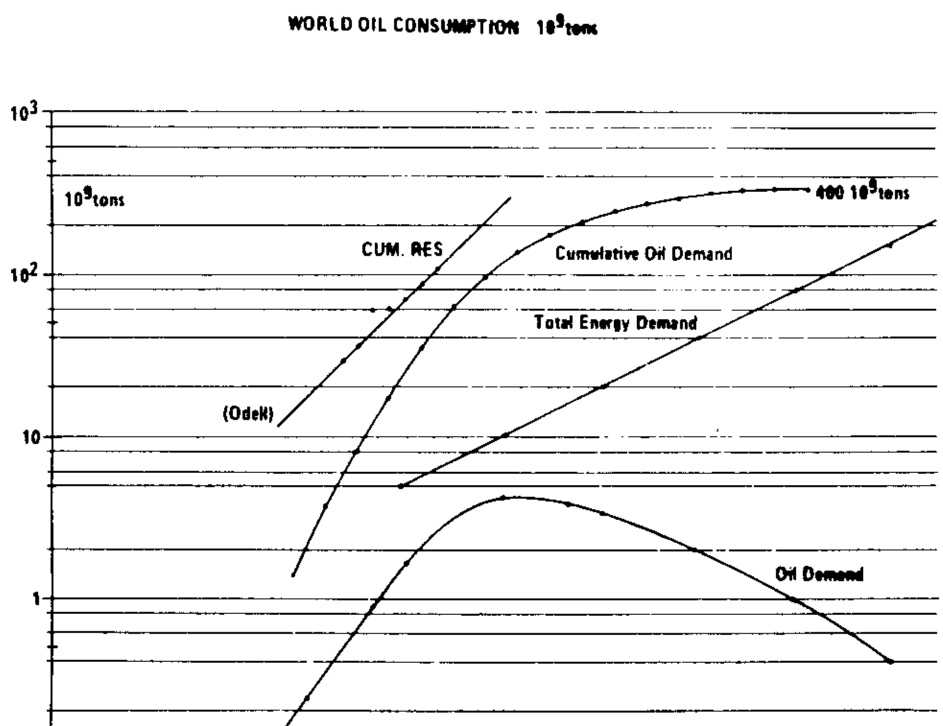

Fig. 7. Oil consumption in 10^9 tons in current and cumulative terms. Total energy demand comes from Figure 5, market shares from Figure 3.

per year. The integrated amount extracted during all of the coal-age cycle will amount to ~300 × 10^9 tons, of which ~200 × 10^9 tons are already extracted. As people are now so sensitive to deaths linked to energy use, it is interesting to calculate how many people will die just to extract that other 100 × 10^9 tons. My back-of-the-envelope calculation is about 200,000, taking into account the fact that much coal will be extracted in developing countries.

Figure 7 shows the consumption of oil. Here oil demand is at a maximum now and will stay basically the same for another 20 years at a little below 3 × 10^9 tons. I must warn that the figures in the chart are smoothed because total energy consumption has been smoothed by eliminating the Kondratieff perturbations that clearly appear in Figure 5. Integrated oil demand will go to an asymptote of 400 × 10^9 tons of which only about 100 × 10^9 tons have been extracted. Although already at the beginning of its decline, the oil industry has still most of its future in front of it. Demand will still be 0.5 × 10^9 tons in 2100, which corresponds to a *mean* loss of production of 1.6% per year.

In Figure 8 the case of natural gas is reported. Here the figures all appear very large because this technology is expanding into an expanding market. Gas demand will reach its peak around 2060–2070 at the level of about 30 × 10^{12} m^3. This is roughly an order of magnitude higher than the peak for oil, in energy terms. Gas demand would reach the present oil level on its way down only around 2150. The asymptotic level for integrated demand is about 2500 × 10^{12} m^3 *of which less than 2% has already been extracted.*

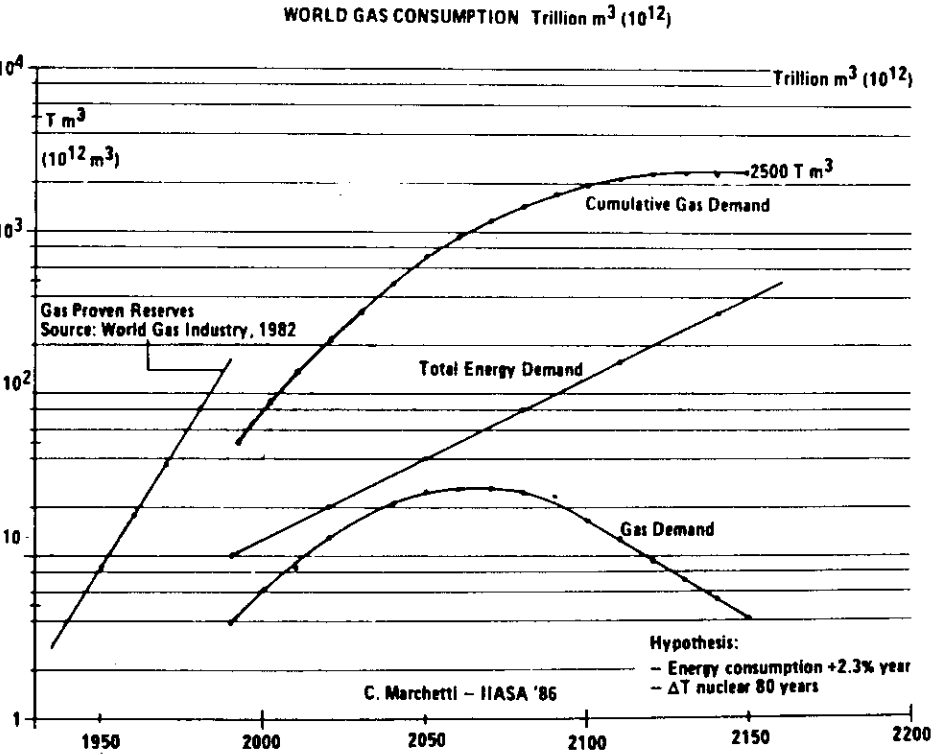

Fig. 8. Natural gas consumption in 10^{12} m^3 in current and cumulative terms. Total energy demand comes from Figure 5, market shares from Figure 4.

On top of the stability of the 2.3% growth for total energy, I made a second hypothesis, that the time constant of penetration for nuclear energy is about 80 years. More or less business as usual. The rate of penetration of fusion, or of something else later on, will have no influence because the rate of decrease will be already set by the penetration rate of nuclear energy. This conclusion derives from the rules of market substitution. Rates of decrease of coal and oil are already set at present.

Because the strength of all these deductions depends on the validity of the hypotheses, let us again look at them critically. The capacity of a system of interacting logistics to predict the market share over long periods of time has been tested in many cases. Figures 9A–C report our classical example, showing that the world market share of oil in 1980 could have been predicted in 1920 with a precision of a few percent.

The growth of a certain commodity, here energy, to fill the "niche" is always logistic, i.e., almost exponential below the inflection point. For energy we are not yet able to calculate the saturation point, so the exponentiality may become weaker toward the end of the period analyzed, leading to an overestimate of consumption, e.g., for the 50 years after 2100.

For the population growth, which serves to check more than to prove, demographers are sure of the next doubling to 10 billion, but have no opinion about the following doubling. This is a typical position of the specialists. I constructed a scenario wherein the earth could accommodate 10^{12} people, [3] just to test the size of the niche. No niche was left half empty during the last four billion years!

How do the figures for integrated demand compare with resources and reserves? For

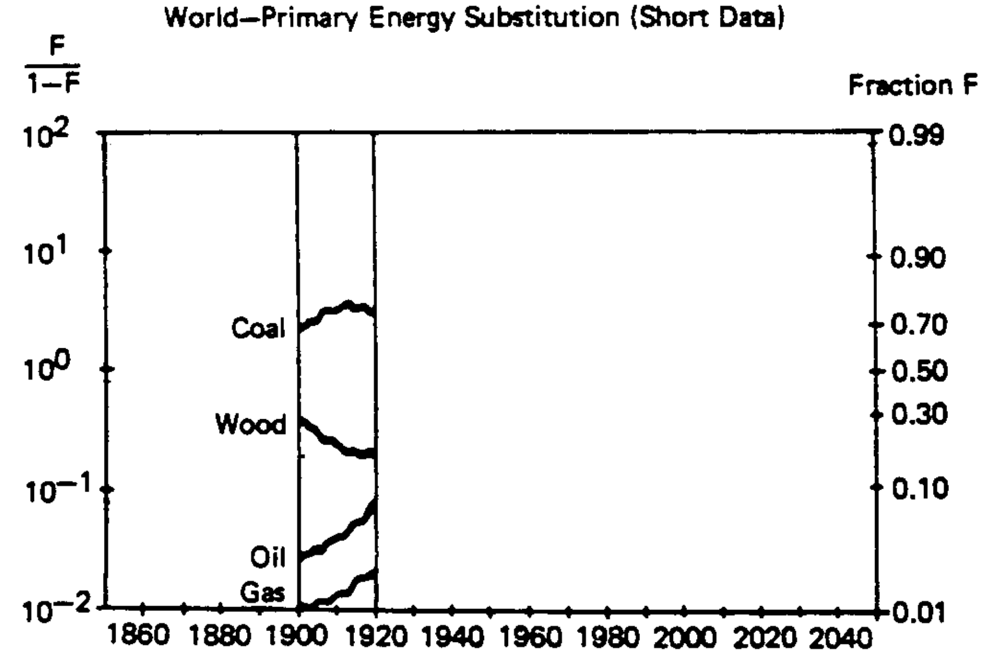

Fig. 9. To show the potential of market substitution analysis to predict, the case of a limited data base (1900–1920) is here reported (Figure 9A), the equation established using this data base (Figure 9B), and the actual statistical data superposed to check the forecasting (Figure 9C). Only gas appears relatively poorly predicted, but this is due to its very low penetration (2%) at the end of the data base.

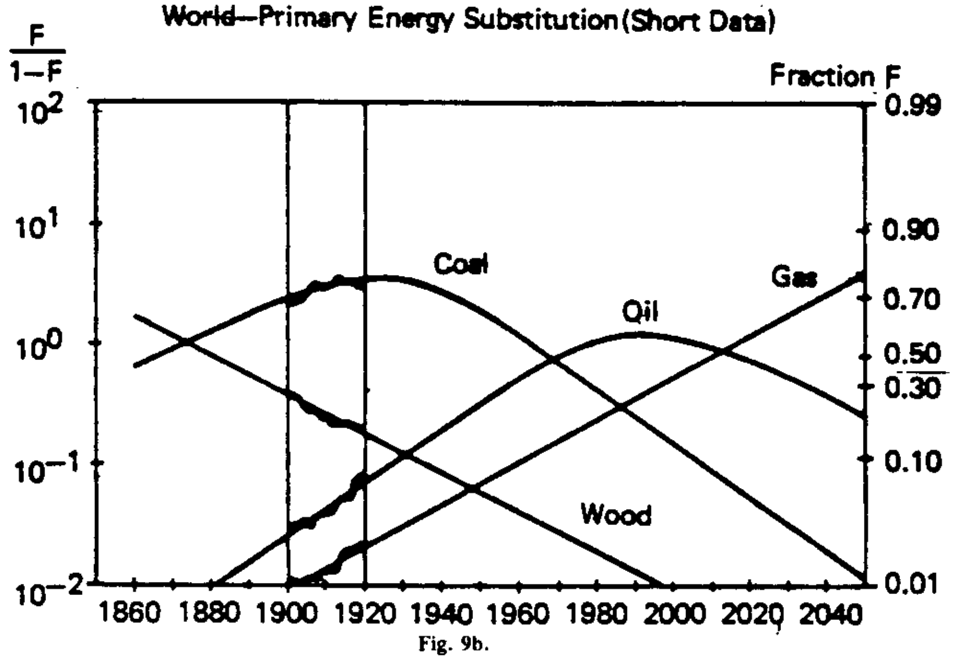

Fig. 9b.

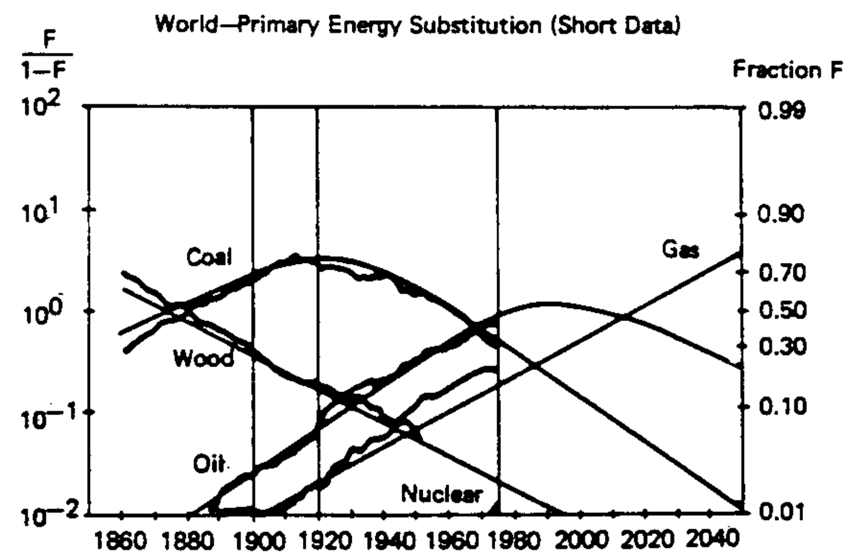

Fig. 9c.

coal there is no problem; 100 × 10^9 tons are already in known deposits. Only logistics and politics may play a role in searching for new ones. For oil the situation is a little more tight, but the 300 × 10^9 tons seem to be there. As Figure 10 shows, the estimates of final resources are a gliding figure going upward in time. Because there is no general theory of oil formation that permits an "external" estimate, one has to drill and look.

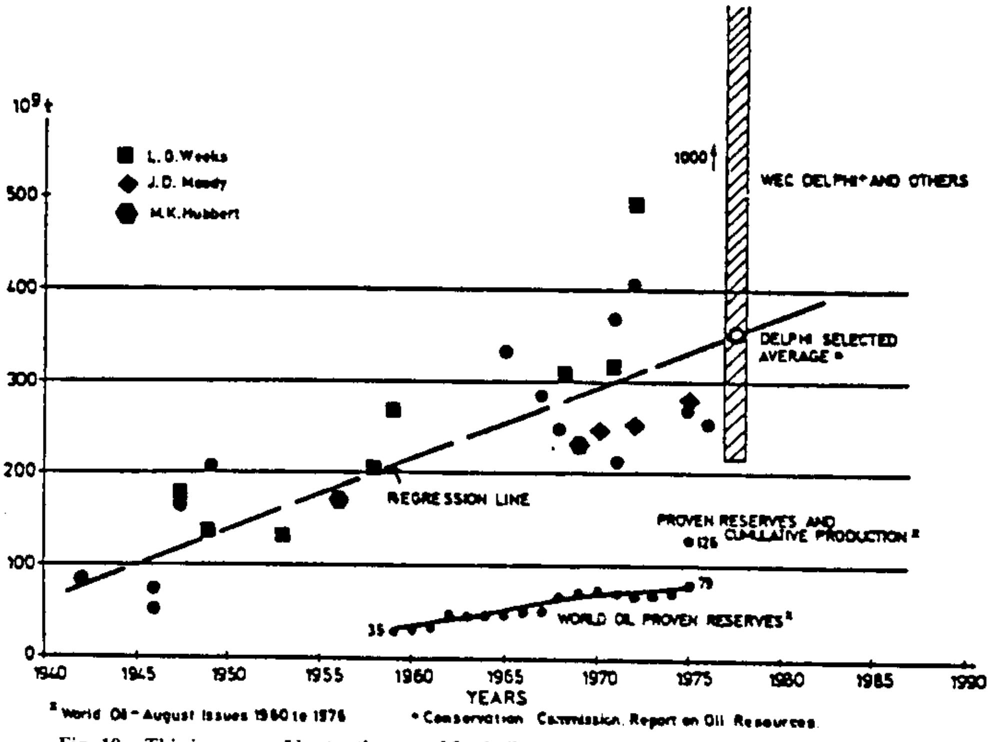

Fig. 10. This is a map of best estimates of final oil resources, given by top range experts at different times. It is clearly an upward trend more or less in tune with exploration levels.

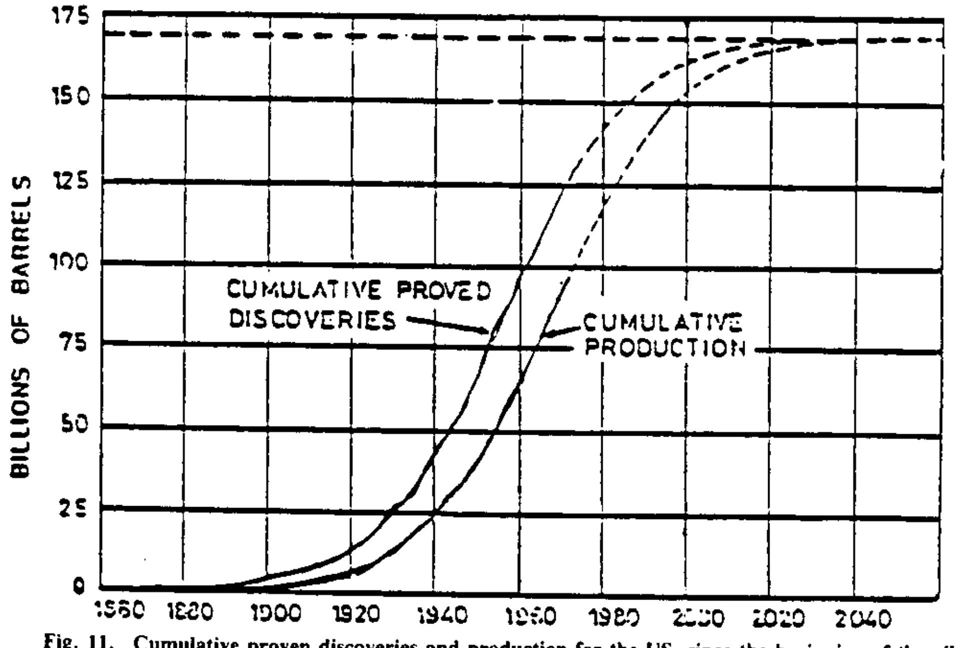

Fig. 11. Cumulative proven discoveries and production for the US, since the beginning of the oil era. It is clear that economics strictly links research to production. The gap between the two curves is a very stable 14 years.

TABLE 1
Drilling Finding Rates (Tons per Meter of Exploratory Well)

Year	USA	Western Europe	Latin America	Africa
1970–1974	7	520	200	520
1960–1964	6	17	57	380
1950–1954	7	40	80	37

Source: Grossling [1].

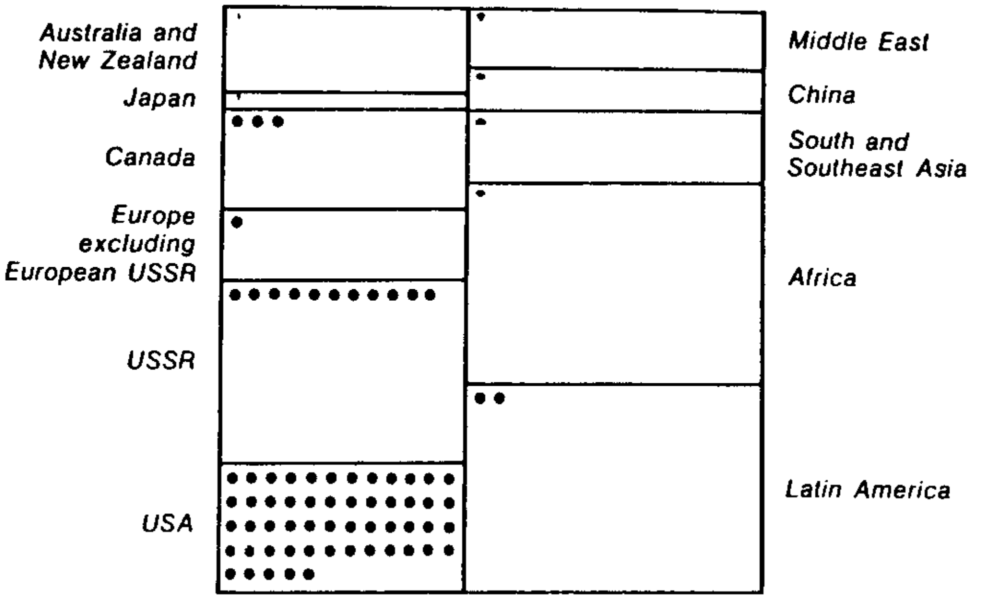

Fig. 12. The best measure for assessing exploration efforts in various petroliferous areas is to map the level of perforation against the extension of the area itself. *Source:* Grossling [1].

TABLE 2
Free World Exploratory Well Completions (Rounded Figures).

Region	1970	1972	1974	1976
North America	9000	9000	10500	12000
Latin America	500	400	400	400
Eastern Hemisphere	700	800	800	800
Africa	250	200	200	150
Europe	150	200	250	250

Sources: American Petroleum Institute and American Association of Petroleum Geologists.


AREAS OF
POTENTIAL OIL
AND GAS OCCURRENCE
ONSHORE
OFFSHORE
Detail varies regionally
depending on data available
Equal area projection
60°
30°
0°
30°
60°
90°
120°
150°

Fig. 13.

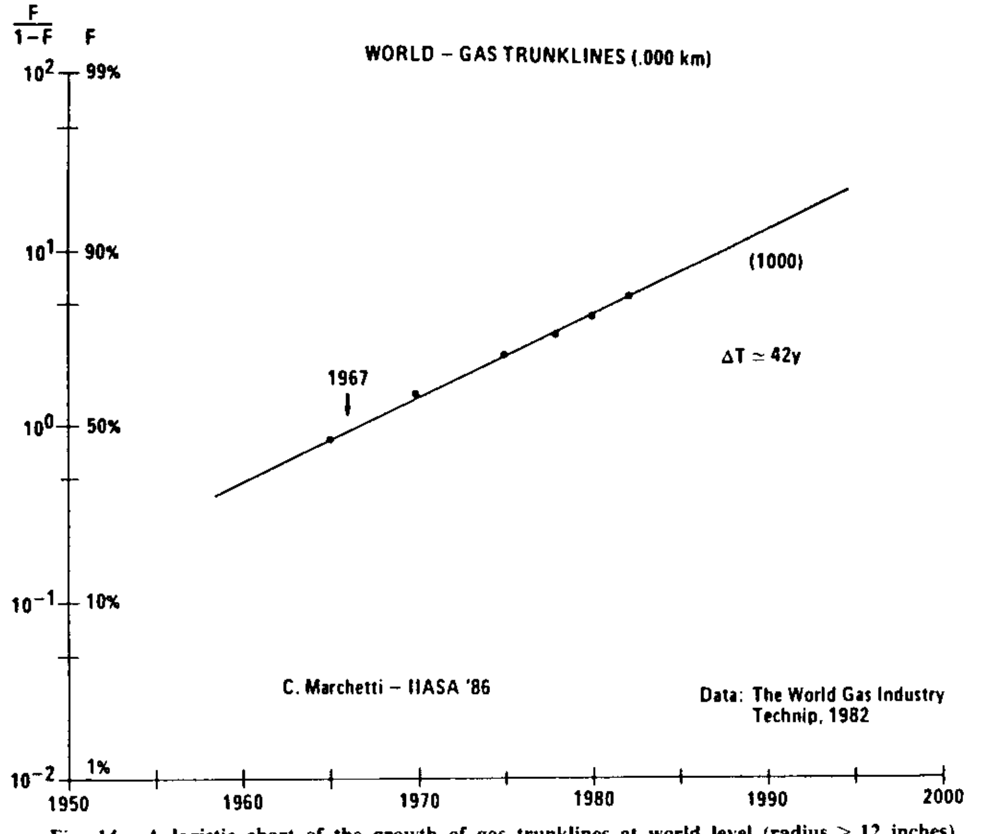

Fig. 14. A logistic chart of the growth of gas trunklines at world level (radius > 12 inches). Saturation point for the present Kondratieff cycle is 10^6 km. Half of that was already in place in 1967.

Since the process is very expensive, consumption is in control of research activity. As Figure 11 neatly shows, oil reserves in the US have *always* been about 14 years, based on current consumption.

In a 1976 publication, B.F. Grossling of the World Bank did show some peculiarities of the process, e.g., that the search for hydrocarbons is much more controlled by geopolitical context than by the probability of discovery [1] (Table 1). The fact that maximum drilling activity is where return on discovery is minimum defies any viable economic explanation. Furthermore, because, as said before, the only sure way to know is to drill, the density of drilling over the areas that in principle may carry hydrocarbons is the best measure of their potential. The situation is reported in Figure 12 and Table 2, showing that most of the world is still virgin, a situation clearly mirrored by data in this table.

The real problem seems to be natural gas. Here the final integrated demand is five times that for oil. It would be consoling to find some geological hint that this can be done. Certainly the arguments Prof. T. Gold is presenting in this meeting are of capital importance and we all pray on our knees that the Siljan drilling project is going to show a gas deposit in primary rock at least as large as Groningen. We need *just one thousand* of them. In the meantime we have to rely on the Grossling logic. Because the present reserves are on the order of 100×10^9 m^3, and the volume of potential gas bearing

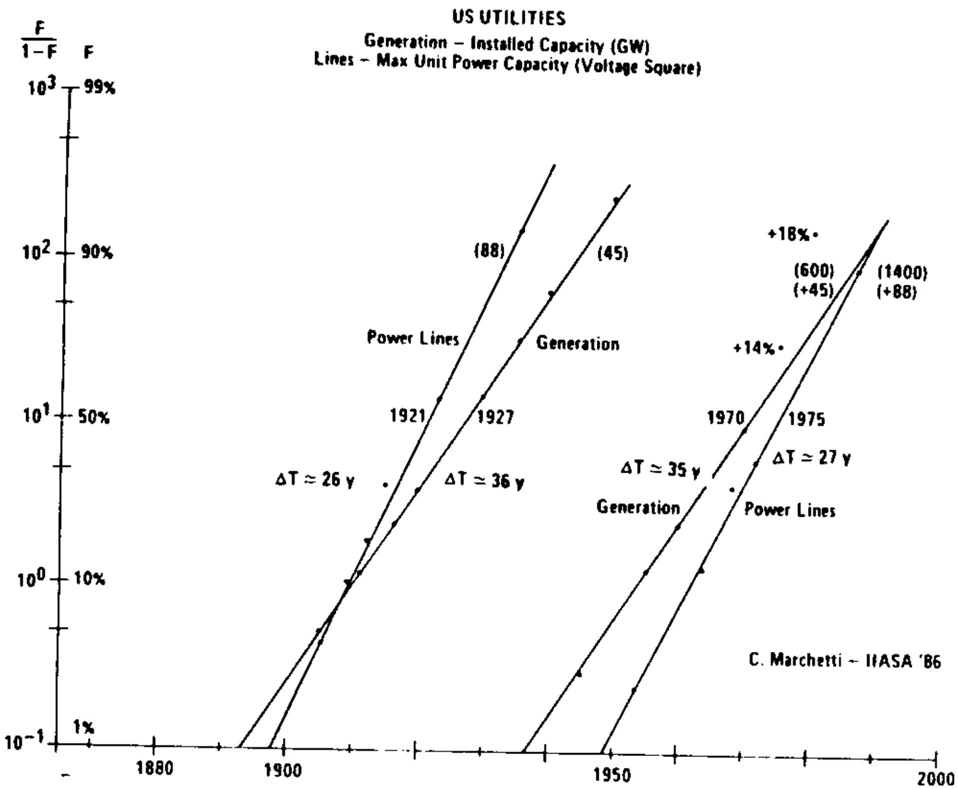

Fig. 15. The next round of gas demand growth will require larger pipelines (eventually up to 3 m radius). The link between the power of the system and the unit transportation capacity is well described by this chart on installed capacity and power line capacity in the U.S. It also clearly shows the effect of the Kondratieff cycle.

formations (Figure 13) already explored (Figure 12) may be on the order of a few percent, the final resource matching the total demand forecast is in the realm of the possible. The recent discoveries are, in fact, delineating new large oil provinces.

After the great excursions into the big time, it may be interesting to zoom back into our lifetime niche, and check what's happening. For natural gas, long-range transportation is somehow the weakest point of the system. World gas trunklines, i.e. pipelines with a diameter larger than 12 inches, are the long distance work horses. Their development is given in Figure 14. The saturation point is about 1 million kilometers toward the end of the century.

This conclusion does not contradict the previous forecasts, because I smoothed out the Kondratieff oscillations. Almost everything "saturates" near the end of a Kondratieff cycle (1995!) and pipeline networks are no exception. Expansion on a new logistic will start again toward the end of the century. Incidentally, because the increase in methane consumed, i.e., transported, is more than an order of magnitude during the next Kondratieff cycle (i.e., 55 years), the bore of the largest pipes (now at 58 inches) should double. This link between traffic and size is very evident, e.g., for electric networks, as shown in Figure 15.

For overseas transportation, much enthusiasm was raised 20 years ago by the first LNG tankers. The trade developed nicely, but not explosively. Figure 16 gives LNG transported worldwide. It saturates at around 60 × 10^9 m^3. LNG tanker fleets should follow a similar trend (Figure 17). It is, in fact, perfectly matched by a logistic curve, saturating at 7.1 million tons, with a similar time constant and central point. The introduction of the technology was very fast and it is by now saturated. We must wait for the next wave (1995) to see if a technical breakthrough or a surge in this type of demand will restart a new logistic.

Zooming still further down, we can see that Europe, with its backbone of gas transport lines, has clearly entered the methane age (Figure 18). It is not yet clear if metropolitan resources will be enough to sustain all that development. Certainly, the situation would look much better if the Soviet Union would come full force into the picture. This possibility is obviously linked to many factors, basically political ones.

A possible way out would be to structure the whole system so as to be resilient to the default of one of the large suppliers. Such a scheme was developed by my collaborators and myself a dozen years ago, [5]. based on the strategic use of inboard gas resources where large reserve production capacity should always be kept alive, and the operation

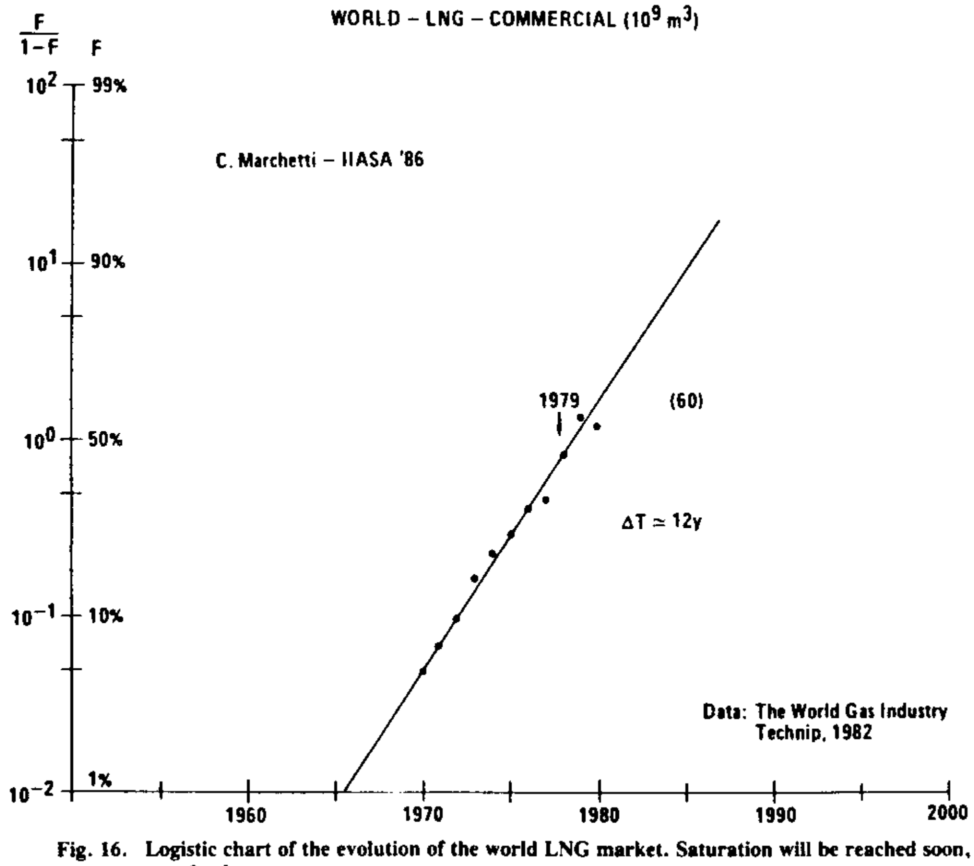

Fig. 16. Logistic chart of the evolution of the world LNG market. Saturation will be reached soon, at around 60 × 10^9 m^3 of gas. The time constant is very short, characteristic of technologies born near the end of a Kondratieff cycle.

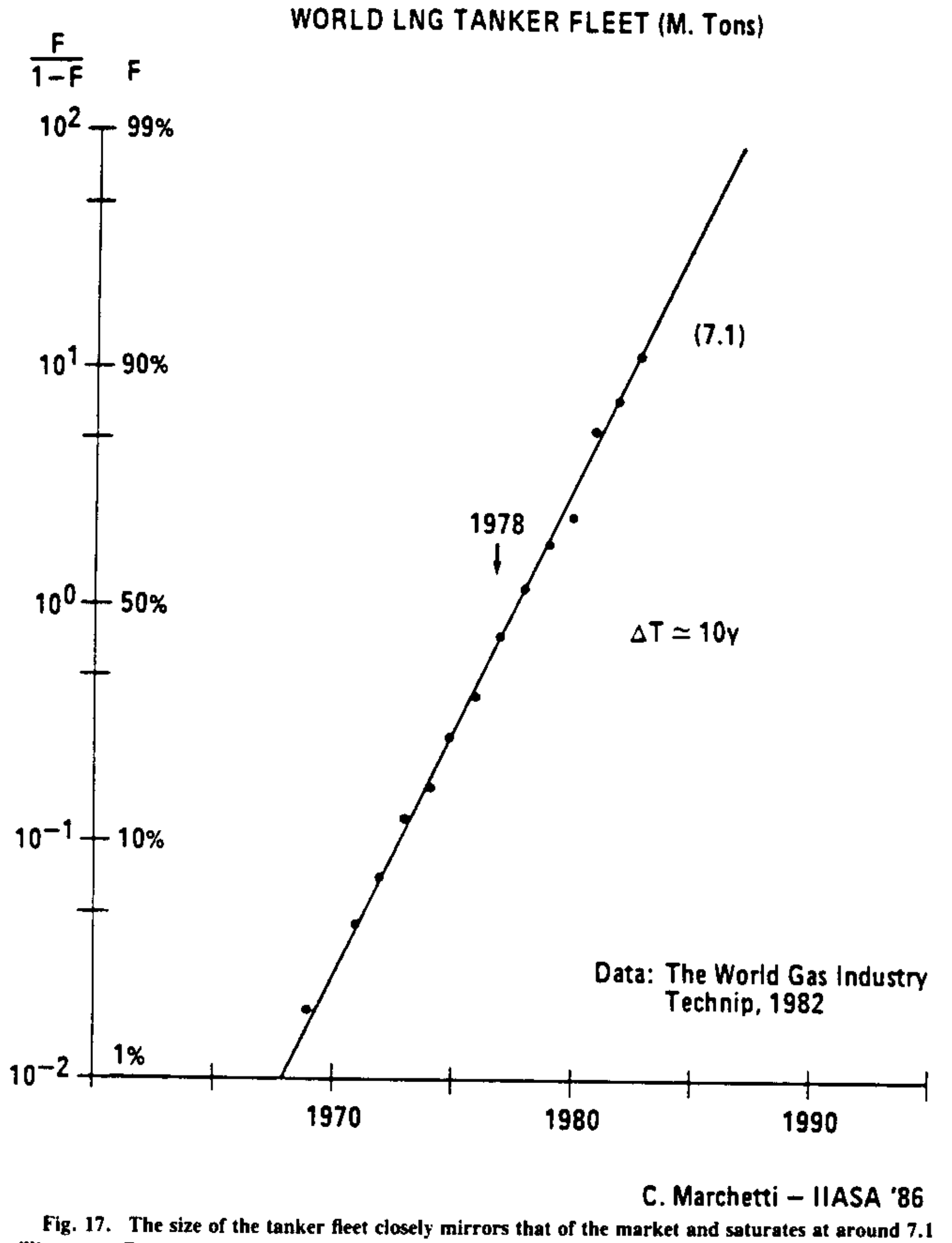

Fig. 17. The size of the tanker fleet closely mirrors that of the market and saturates at around 7.1 million tons. The slightly slower slope than for the market signals a better utilization of the ships, or perhaps a shortening of the routes.

of transport lines (e.g., the Russian ones) at full capacity. Surpluses would be stored in consumer areas. Both procedures are currently in use to satisfy winter peak demand. The suggestion is that we look at them in a strategic mode, at the geographical level of Europe and on a time scale of ten years. *The Soviet Union is an actor that may greatly improve the European play.*

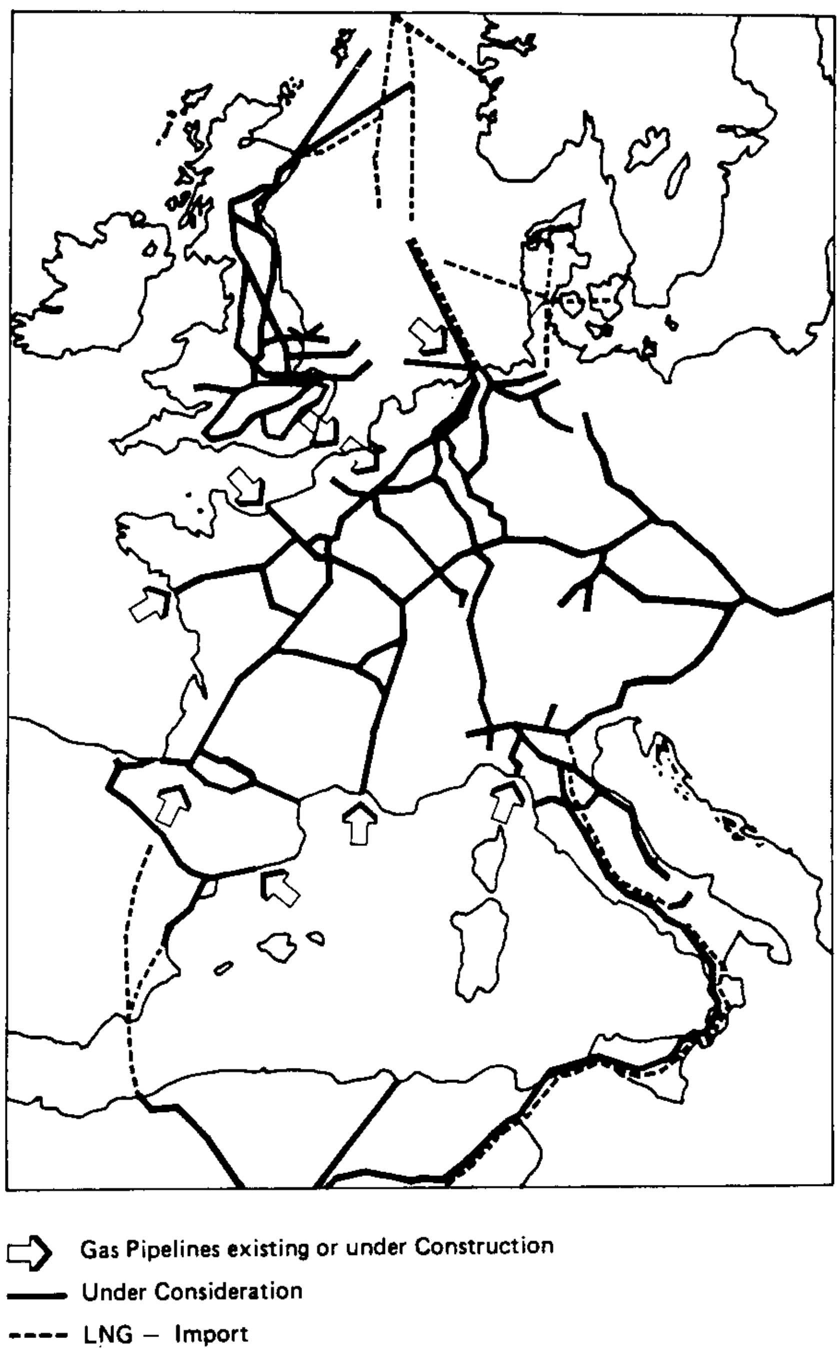

Fig. 18. A map of the trunklines of Europe shows that the basic frame is in place. Connections with the Middle East and perhaps Great Britain would be welcome to fully integrate the picture.

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