The Evolution of the Energy Systems and the Aircraft Industry*

MARCHETTI-26

by C. Marchetti**

Abstract

The driving force for evolution, in the Darwinian sense, are the changes in the external physical conditions and of the biological context. The aircraft industry, so alert and dynamic, senses that important changes are coming and tries to preselect the proper mutation to face them.

The scope of this paper is to draw a long-term picture of the energy system, technology and aircraft evolution, and to try to evaluate, by meshing the three, the necessity and the chances of a LH_2 fueled commercial airplane.

The conclusions are essentially positive, although — as we shall see — the logic and the arguments substantially differ from the ones in the current literature.

The Energy System

The energy system can be defined as that complex socio-economical web that makes available to the final consumer, in proper form, free energy stemming from some primary resource: wood, coal, oil, gas, hydro, and nuclear. I said on purpose socio-economical, because it is there where the causes are sitting and operating, and where rules and laws get their shape.

The starting point of my consideration is deceivingly simple. Introducing coal or oil at the level of human society, or of the British railway system, or of the citizens of Frankfurt, is a learning process. Learning processes have, in general, a temporal dynamic described by logistic functions[1].

Learning and unlearning toward a certain objective can be in the form of multiple parallel processes, and also here a properly managed set of logistic functions can describe the evolution of the system. The situation is best explained by an example (Fig. 1). Here we describe how humanity learned to use fossil fuels taking as an indicator the fraction of the total energy market covered by each one of them as a function of time. The fitting curves are basically logistic equations of the type log F/1-F=at+b, with some rules for assembling them in a system better described in[1]

In system terms, coal or oil are quire abstract conceptualizations, enveloping an extremely complex mixture

Fig. 1 World-primary energy substitution

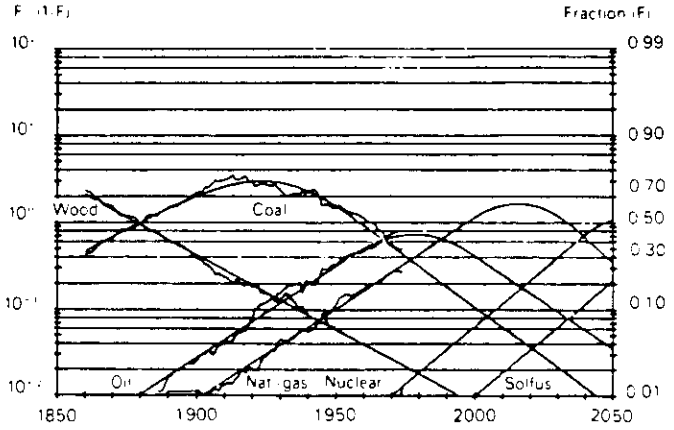
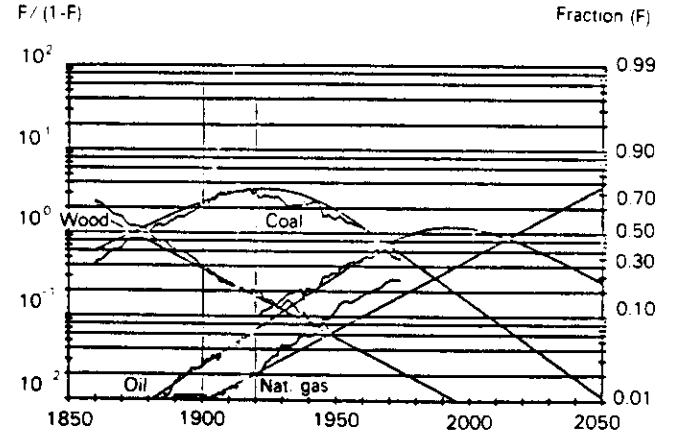


Fig. 2 World-primary energy substitution (short-data)



of technology, geology, geography, politics, and history. However, the fitting to the logistic function is just as perfect as that of the development of the vocabulary of a child. And the cause is not global aggregation. The same is true for all sorts of smaller aggregates we tested (about 300 to date)[1]

Our logistics are two parameter functions and consequently we need only two points for each one to completely determine the set. In order to smooth out the noise in the statistical data, we need in fact a few more, but not many. In Fig. 2 we took data within the time span of 1900-1920 and we used them to fit the basic logistics. As one can see, the curves can extract information only from a 20-year period, but they map with unexpected precision 150 years of data. Just as a counterproof, we took for the data base the post-war years, which many people like to consider as revolutionary and discontinuous with the

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** *International Institute for Applied Systems Analysis, Laxenburg, Austria*

past, and projected the equations back, with the same extraordinary result.

I'm showing these results for various reasons, the most important being to de-emphasize the oil shock. An oligopolistic manipulation to modify the income flows at world level cannot be more disruptive than World War I and II or more pervasive than the great depression, events that made no lasting dent in the secular evolution of the system. Furthermore, the system did not change gear after World War II, so after all the equations could be good for another 50 years, which is the time horizon relevant for the next generation or two of airplanes.

Armed with this grain of faith, let us look again at Fig. 1. We see primary resources coming and going in our energy budget, and we can wonder about the causes. "Exhaustion" is the current password. It has the advantage of being easy to grasp. The bottle of champagne is empty, let's drink Vichy water. It has the disadvantage of having no relation with the facts. Oil would be much less important whatever the resources are if, for some reason, it could be carried only on camel back. Primary production of world forests is an order of magnitude larger than total energy consumption by man, but the mule back technology to which it is linked relegates wood (now biomass) to a very secondary role. And the decreasing role of coal, which started in the twenties, can be hardly ascribed to a shortage of resources.

I found a great resistance to assimilate this concept from people used to the much simpler idea of the dry tank. Why should gas be not available if the tank is not dry, is a non-intuitive situation and I will try to explain it with an example. Road transportation for goods has progressively substituted rail transportation in the last 50 years. Considering the capacity of the rail system as a resource, and an extremely valuable one in terms of rights of way, we see that it is less and less exploited in time, despite the fact that, on paper, rail transportation is so much more economic and the potential is so large. The fact is that, for historical reasons that tend to repeat, the railway organizations progressively lost contact with the external world, first through the insolence that naturally comes from a

Fig. 3 FRG-secondary energy substitution

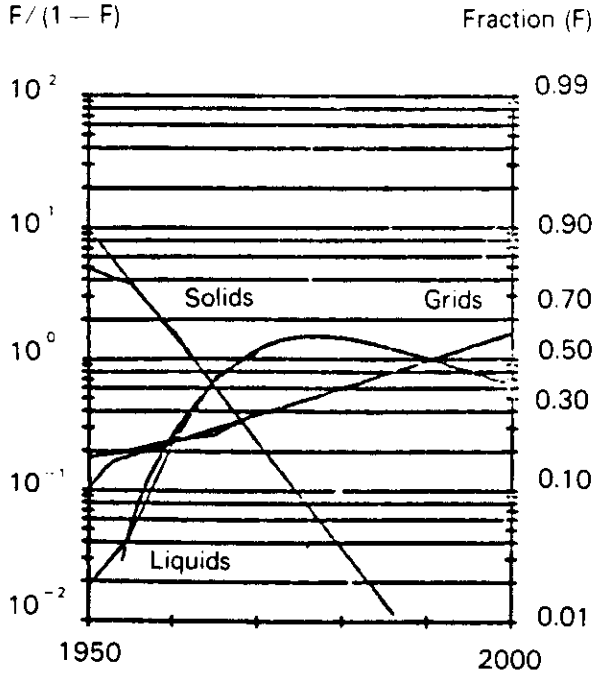
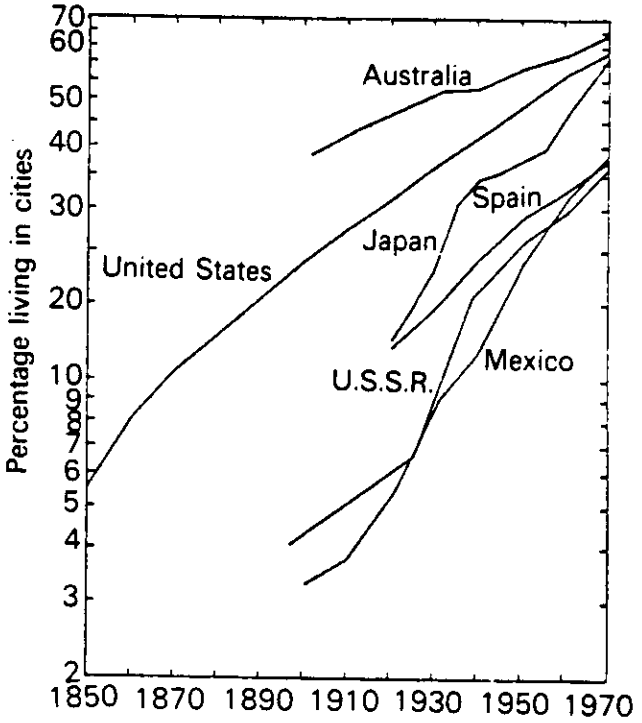


Fig. 4 The percentage of population living in cities



monopolistic position, then through the negligence induced by the apparent stability of a system that cannot grow and which degrades very slowly.

Oil can outmarket itself in many ways, e.g. through insolent price manipulations and neglect of contextual evolution. As we see in Fig. 3, which looks at the form under which energy is delivered to the final consumer, in Germany nets are progressively substituting the liquid and solid form of delivery. The driving force here is the implosion of population into the cities, a world-wide phenomenon nowadays (Fig. 4). When the spacial density of consumption reaches a certain level, the network becomes superior to lumped distribution, and completely eliminates it, in time. Energy consumption is basically concentrated in the cities, and gas is the only fuel perfectly suited to net distribution. We see here a clear mechanism at work, and at work everywhere. As observed by W. Häfele and W. Sassin of IIASA[2], the spacial energy consumption (kcal/m²) in a city is substantially independent of the level of development of the nation to which it belongs, higher population density neatly compensating for lower per capita consumption so that the phenomenon is worldwide.

Contextual evolution will tend then to concentrate demand on natural gas, in accordance with the phenomenological equations.

Where all that gas will be found is the ritual question and my relatively naive answer is: underground. Gas is more likely found in deeper basins, for economic reasons the less explored and exploited ones. But new technologies for bringing these basins within reach are mature at the laboratory level and will make their impact felt in the next 20 years[3].

Natural gas will be followed by nuclear energy, which has already its foot in the door, if not more, and as a consequence gas will end its penetration and start reducing its market share around year 2010-2020 (Fig. 1), a not too far away point in time

even for a fast moving technology like the aeronautical one.

When a technology saturates there are remarkable troubles in the pricing system. US coal doubled its price abruptly in 1920, at the top of the penetration curve, and so did oil with a fourfold increase in 1973. One is tempted to say that the troubles of the oil market will resound in the year 2020 in the gas market.

Nuclear has not penetrated enough to fix the second parameter in its equation. We assumed business as usual, as the system appears so stable. A rate of market penetration equal to that for oil and gas gives about 6% in the year 2000 and a dominant position in 2050. If we look long-term, then nuclear provides a safer foundation for a dependent technology than gas itself.

A second ritual question is what happens with coal. Coal in the classical sense is obviously on its way down and all the noise uttered during the last 15 years does not seem to have had any impact on the facts. The logistic model, however, does not predict the development of a new technology which is an external input to the model; consequently a completely new technology based on coal is always possible although I do not see any sign of it coming. I cannot, on the other hand, rule it out on general principles. After all, *thermodynamically* one could transform coal into benzene, if only the right catalyst was available, or coal plus water into methane and CO_2 under the same conditions, just by mixing and shaking. What the logistic model can say is that *if* this new technology is introduced on a large scale in the year 2000, it will become dominant in the year 2100.

At this point I hope I condensed a sufficiently simple and easy to grasp image of the future of the energy system structure. The most extraordinary fact is that its description does not require the concept of prices. This opens up a very serious question. If prices are contextual and not causative, we may have to sit in the wilderness for a while as energy oligopolies appear quite strong. If prices are just eliminated because price *ratios* are kept constant through market mechanisms, then all proposals based on "cheap coal" and retrograde competition, like making synthetic oil from coal, have a very low survival probability.

The Aircraft Indusry

Wrights brothers' flight can be considered the professional

Fig. 5

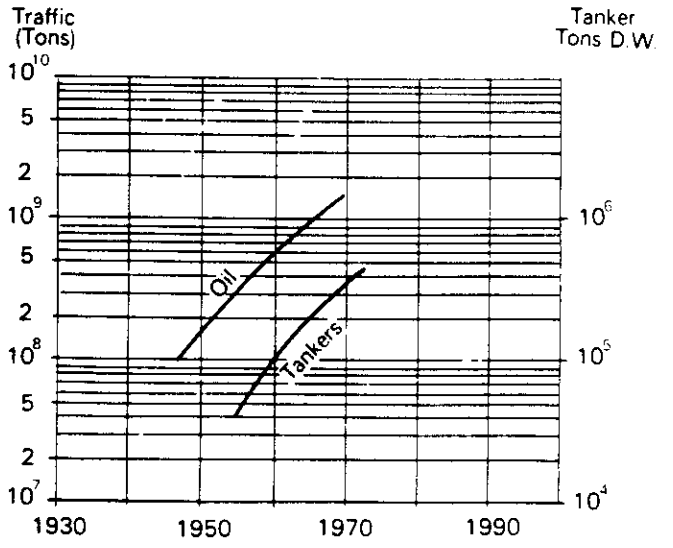
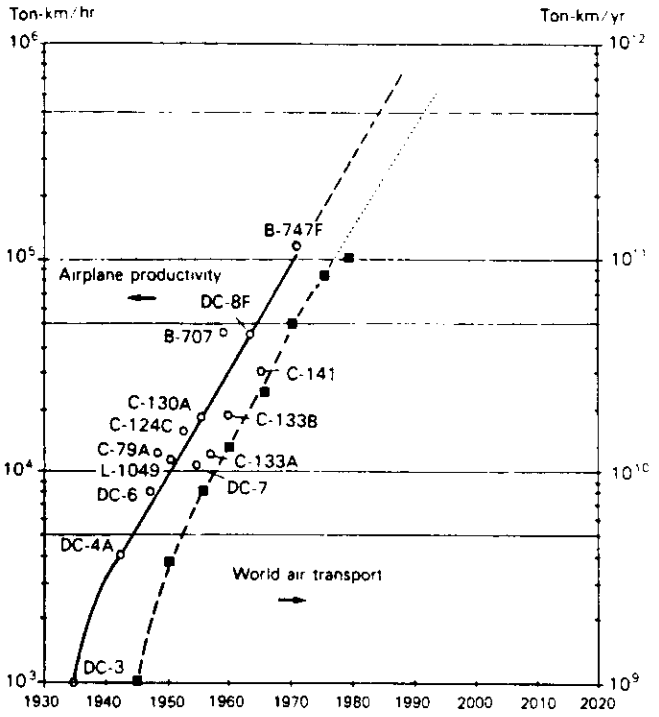


Fig. 6 The air craft and the market



start of aviation. It caught the imagination of inventors and broken necks, spurring an incredible amount of innovation and experimentation. Even the jet engine, in a fairly modern conception, was invented in that period and patented in 1912.

World War I, with a lively demand in sturdy and dependable craft, can be considered as the beginning of the aircraft industry. The post-war period saw a flourishing in airmail traffic done with small planes and sporty pilots. Passenger traffic started very timidly in that period. One had to be fit and courageous. In 1926 the passenger miles flown were just one million. I did substantially better, all alone, during my flying life.

One may think that flying was poor because the technology was immature. I would reverse to a point the argument and say that planes were poor essentially because only few could afford them. Said in this form, the argument in overstretched, but I want to emphasize market forces.

Engineers usually think they are the driving cog of technological progress, but historical analysis tends to disprove that tenet. To show a very explicit example, it was not the progress in shipbuilding that led to supertankers of increasing size, but the evolution of optimal size of tankers in relation to the evolution of the market that induced the progress in shipbuilding as clearly shown in Fig. 5. The same occurred in aviation. Here planes are better characterized by their productivity, i.e. ton km/hr, because contrary to ships, planes have had a wide range of speeds. As shown in Fig. 6, the productivity of planes followed tightly the evolution of traffic. *We can easily forecast the productivity of planes in 2020 if we have an idea of the traffic then.*

As people tend to allocate a reasonably constant fraction of their time and income to traveling, the increasing income level in the world will lead to an increasing share of time traveled in the most expensive, but most efficient, traveling mode.

Even with relatively modest growth levels in income, say 2%

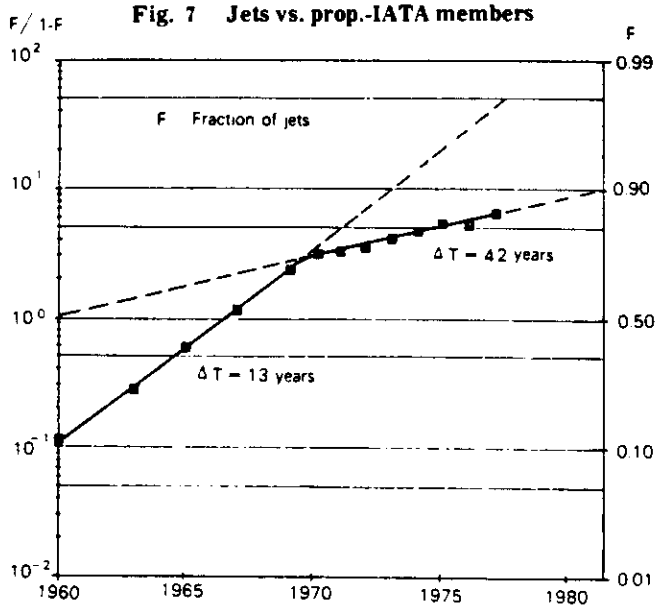


Fig. 7 Jets vs. prop.-IATA members

per year in real terms, airtraffic will grow at least 5% or 6% per year and we should expect an order of magnitude increase in airplane productivity before the year 2020, which is not so far away in terms of airsystem time constants as we will see in a moment.

An order of magnitude increase in productivity means planes ten times larger (5,000 seats) or ten times faster (Mach 9), or most probably a compromise between the two. Let us salomonically compromise on a plane three times larger and three times faster than the present top performer, the 747. With current technology this Super-Sonic-Super-Jumbo would have perhaps 1,000 tons of fuel at takeoff. It is clear to me from this detail alone that the system is calling for a new technology in the fuel system. LH_2? Liquid hydrogen has in fact many other points to recommend. Apart from the low specific weight which automatically increases plane productivity, the frigories it carries permit sophistications not otherwise possible, like the cooled wing capable of operating in laminar regime with great energy economy[6, 7]. The real problem is who will take the initiative and the risk of investing at least 10B$ in R&D to develop the prototype. On the other hand, failure to do that will deoptimize all the air transport system with much larger expenses to readapt the infrastructure in order to accommodate a larger number of planes and to operate them. *Perhaps the conscience that world air transport operates like a system may induce subsystems to provide the insurance money necessary to shelter a possible if improbable failure of the air frame company involved in the R&D.*

As I said above, year 2020 is not so far away in terms of the airsystem time contant, and I would like to clarify this point. Aircraft industry prides itself of very high technology and very high capacity in generating and assimilating progress. Let's look a little further into that. After all, the fact that the jet engine was adopted 40 years after its invention may cast some shade of doubt on such tenet.

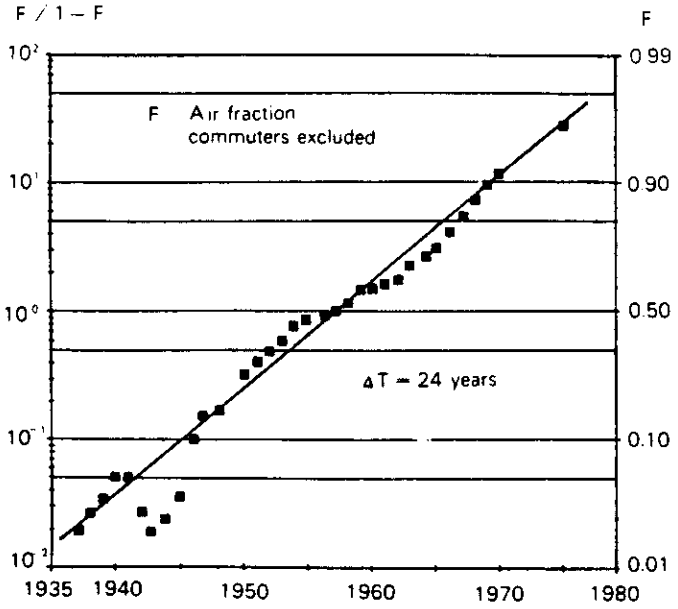
The reason why the jet engine was not adopted before is simple to me: The productivity level that the market was imposing on the planes called for power levels that the piston engine could satisfy. And it is a general rule in innovation, including scientific innovation, that no new idea is bought as long as patchwork can help. The power-hungry fighter planes were actually the material cause of the introduction of the jet engine, roughy in 1942.

Now let's look, once made viable, how fast the jet engine was adopted by commercial aviation. The first commercial flight was in 1952, with the Comet. It happened to be a bad start because of problems in the airframe, but it "caught". The market penetration of jet substituting prop project nicely back to that date (Fig. 7). The most interesting feature in that figure, however, is the time constant, i.e. the time necessary to progress from 1% of the market to 50% of the market. With a time constant of 13 years, it takes 26 years for a practically complete substitution. If the first plane of the new generation is going to fly in 1990, which is not overly pessimistic, these 26 years bring 2020 neatly into focus.

As the aviation system feeds by subtracting travelers (traveling time in my optics) to other modes of transportation,

Fig. 8 Substitution of plane for train in U.S. intercity traffic

U.S. air vs. rail passenger km



Intercity passenger km in U.S.

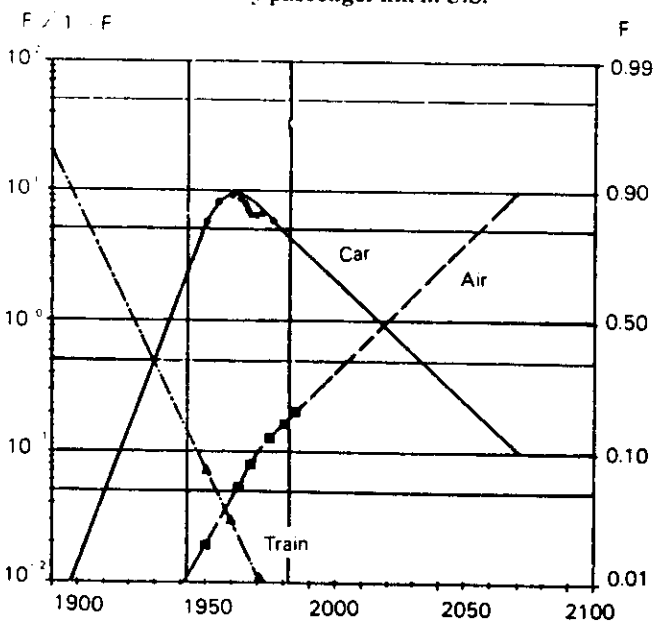
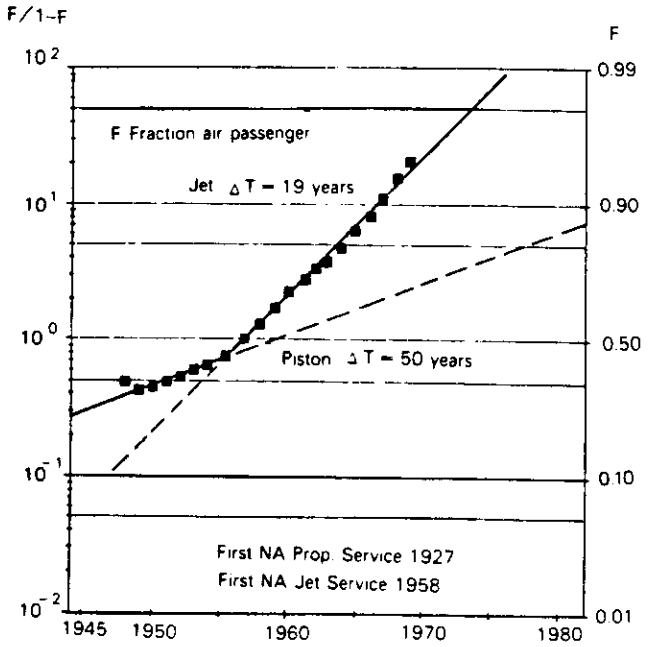


Fig. 9 Air vs. ship-North Atlantic passengers

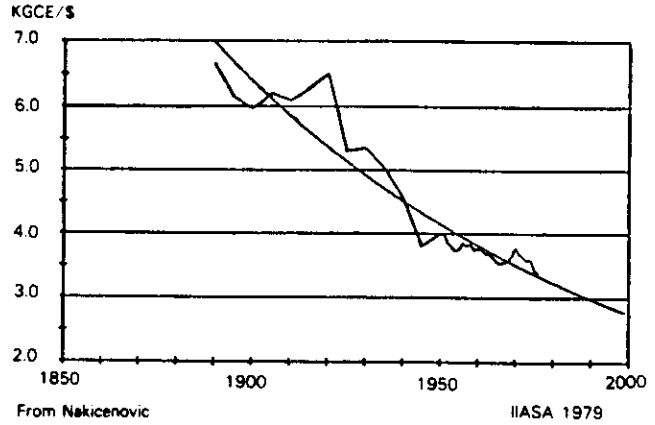


it can be interesting to look at time constants for this process too. The substitution of plane for train in the United States intercity traffic is given in Fig. 8. Here the constant is 24 years. That means it took only about 50 years, with a neat oblivion of the World War II interference, to fill that space.

Another interesting case is that of transatlantic passenger traffic. We see here a curious phenomenon (Fig. 9). The substitution, started with piston engines, had a characteristic time of 50 years, but suddenly dropped to 19 years when the jets were introduced. More properly, this curve should be drawn with three competitors fighting: ship, prop, and jet, the jet appearing as a distinct entity from this type of analysis.

These time constants are external but obviously influence the internal ones and tend to tune them. They bring us again into the 2020 area, which once more appears to be only one cycle away.

Fig. 10 U.S.-energy per GNP in 1958 dollars



On Energy and Aviation

Despite its great visibility (and audibility) aviation does not appear to be a gas guzzler. In absolute terms, because with a consumption of less than 100 MT of fuel (1977) it barely reaches 3% of world oil consumption. In relative terms, because — as has been widely publicized — a passenger-km on a 747 requires more or less the same fuel as on a car, in spite of the greatly superior performance.

There are, however, two snags in this reasoning, at least if one looks at the problem from my point of view.

The first is that what the passenger buys is not really kilometers but efficient travel *time*. This time is, helas, an abundant order of magnitude more expensive, in energy terms, if spent on a plane than if spent on a car.

The second is that one buys this expensive time obviously only when one can afford it, i.e. when the *income* is in a certain (weighted) region on the high side of the statistical income

Fig. 11 OECD Europe-primary energy substitution

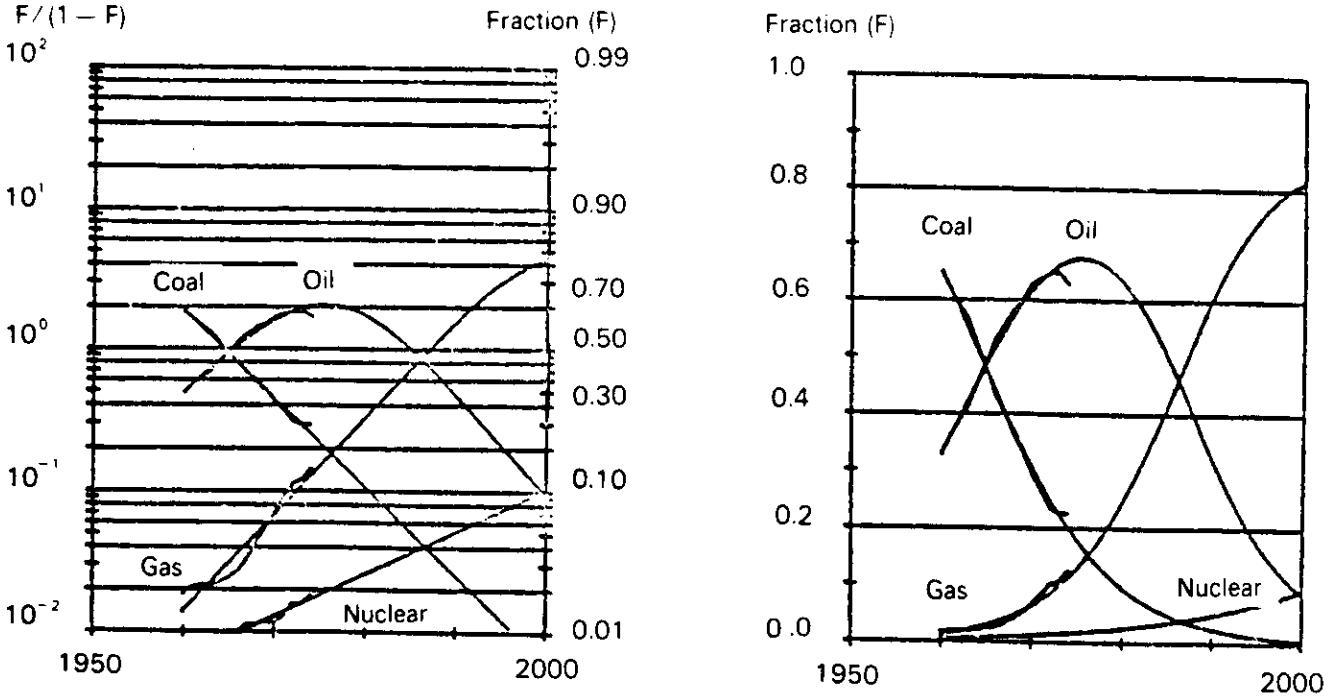
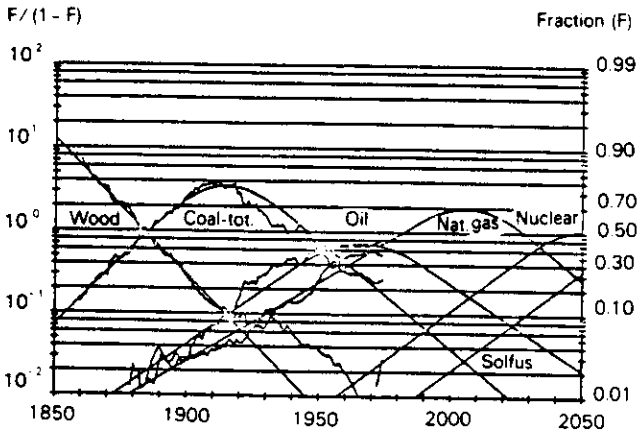


Fig. 12 U.S.-primary energy substitution



distribution. This distribution is usually lognormal and the population with an income above a certain reference level grows faster than the global income. Energy consumption per unit of income, on the other hand, decreases in time (Fig. 10). *Consequently, airtransport is bound to absorb a rapidly increasing fraction of the energy budget.* Furthermore, much of this penetration will occur before the year 2020.

If my logic is correct, and I feel it is, then no palliative will work. More efficient engines, more refined aerodynamics, higher load factors, will only be a little grease here and there. The air industry has to face the fact that within a foreseeable time it will become one of the largest energy consumers and prepare for a controlling position by respect to the fuel suppliers, i.e. take an active role in the process of fuel procurement.

Now what descends from the previous considerations is that:

— Coal is on its way down and up to now no amount of talk has been able to stop its downfall. It is technically possible to produce "synthetic" oil from coal. However, retrograde competitions like this have little chance of success, because the price of coal seems to be locked to that of oil, presumably via parallel competition mechanisms (when both are used in a boiler for instance).

Oil appears to be in the troublesome age of maturity moving toward phase-out from its dominant role. Short-sighted price manipulations are the most probable phase-out mechanisms in my opinion. One should not forget that the difference between the 20 cents/bbl cost of oil in the Middle East, and the 30$/bbl landed price is mostly of fiscal nature, the same as for the 100$/bbl we pay our gasoline at the pump. Fiscal systems are of ratcheting nature. As I pointed out for wood and coal, resources are not really the point.

Gas has a brilliant medium-term future. The fact that the world commerce in LNG will presumably keep increasing may be a temptation for the air industry, as LNG will already be available as a cryoliquid the world over, with obvious logistic advantages. A Damocles sword can be the year 2020 saturation in market penetration, bound to repeat what is happening now with oil. It certainly appears a far-fetched proposition, but having witnessed the incredible doggedness and automatism of system reflexes in the last 100 years I cannot avoid thinking it will happen.

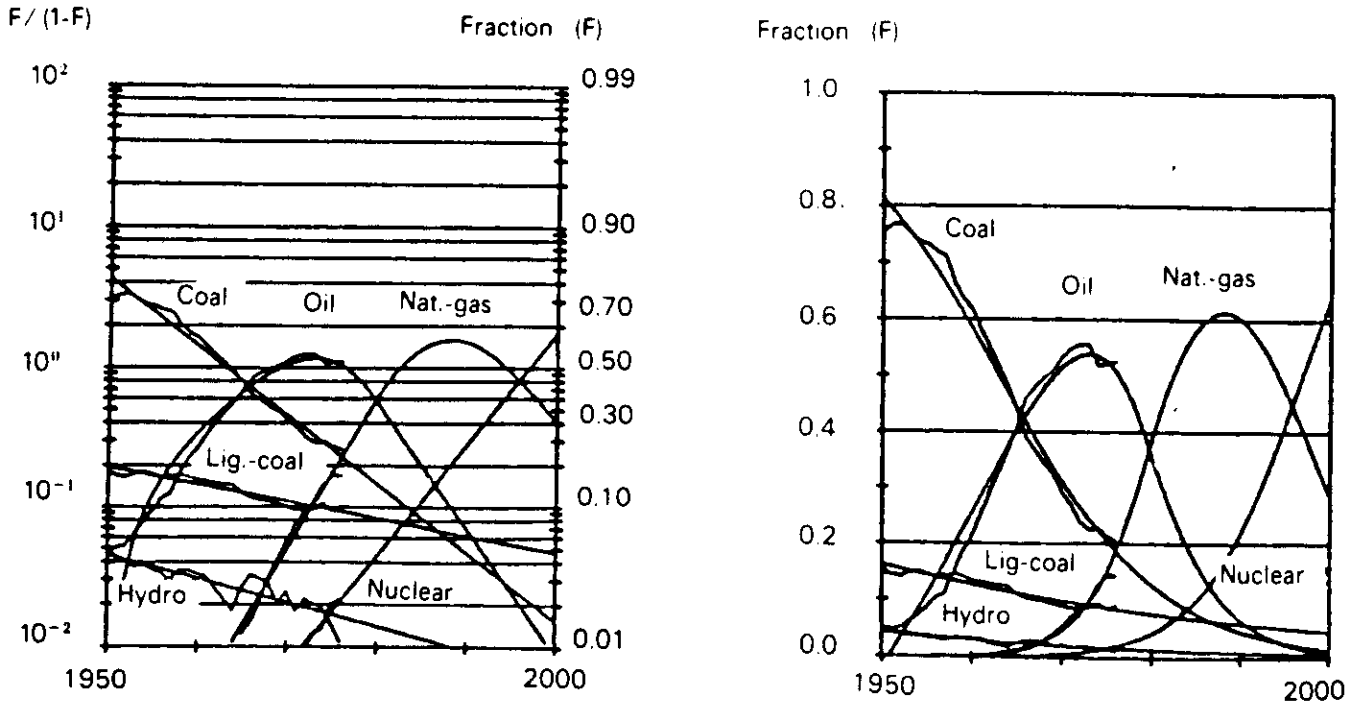
Nuclear will poke ahead to victory, being in time substituted presumably by the fusion variant and perhaps by solar. It will dominate in any case the next century. If nuclear, fusion or solar, are dominant, fuels for aviation have to be synthetic, and most naturally LH₂.

Conclusions

The choices air industry faces are now clear, at least to me, and weighted.

It can *grudge at the oil* blackmail and pass the price to its customers, as it is doing now. This has two drawbacks, first that

Fig. 13 FRG-primary energy substitution



business, i.e. growth will be lost that way, second that blackmails, not efficiently countered, tend to spiral up.

Oil is loaded in any case, and phasing out. Our phenomenological equations predict it to be reduced to 10% of the energy budget in year 2000 for OECD Europe (Fig. 11) and in the year 2020 for the United States (Fig. 12). In the FRG this point should be reached in 1990 (Fig. 13).

Last, but not least, *oil may not be the most appropriate fuel for planes having a productivity an order of magnitude larger than the current ones.*

It can try to *join the gas* bandwagon. LNG has many attractive features from the operational point of view, although the excessive density of vapors emerging from the liquid makes its safety questionable in case of accident or mishandling. On the other hand, LNG could serve a generation, or two at best, of airplanes before pricing troubles begin again. It may pay or not. I have really no feeling.

Going straight to LH$_2$, the step is a little long, but if successful, it promises the *longest pay-off*. LH_2 is the almost inevitable synthetic fuel from nuclear or fusion primary sources. LH_2 is potentially the most efficient fuel for Very High Productivity Planes which the market will demand in the next round (if spiraling fares do not dampen demand).

The source of this hydrogen is really immaterial at the start. All primary sources should have a go and try their chances. Coal may after all have some advantages in this forward competition with oil and gas. Nuclear is the best bet, long-term, and I can well see each airport associated with a proper nuclear reactor, the cost of LH_2 being then substantially stable over the lifetime of the plant.

But let's wait and see. As Darwin quite sharply pointed out, *the struggle for life is the only final judge*

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