THE CONTRIBUTION OF OIL AND GAS FOR THE TRANSITION TO LONG RANGE NOVEL ENERGY SYSTEMS

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Abstract. For medium and long range considerations of twenty to fifty years, i.e. up to the years 2000 and 2030, the growth of energy demand should be considered in a global context. Interdependence will grow. In the study 'Energy in a Finite World' of the International Institute for Applied Systems Analysis (IIASA), Austria, demand and supply scenarios were elaborated in detail for seven world regions. One of the striking features of these scenarios is the strong and significantly increasing demand for liquid or gaseous hydrocarbons despite energy conservation and substitution measures. On the supply side this means more and more unconventional fossil fuels such as shale oil, tar sands and low-grade brown coal. In this paper we consider a transition from the current energy systems to novel fossil energy conversion and distribution systems that will contain all of the mass streams and thereby avoid environmentally hazardous emissions. It is then natural to extend these considerations to prospects for a sustainable hydrogen-based energy system in the far future which would not be constrained by resource limitations.

Résumé. Pour l'étude du moyen et du long terme de 20 à 50 ans, c'est à dire allant jusqu'aux années 2000 et 2030, il importe de considérer la croissance de la demande mondiale d'énergie dans un contexte global. L'interdépendance va croître. Dans l'étude 'Energy in a Finite World' de l'Institut International pour l'Analyse des Systèmes Appliqués (IIASA), Autriche, des scénarios d'offre et de demande ont été développés en détail pour sept régions du monde. Un aspect particulièrement significatif est la demande générale croissante en hydrocarbures liquides ou gazeux malgré les mesures d'économie et de substitution d'énergie. Sur le plan de l'approvisionnement, cela signifie l'utilisation croissante de combustibles fossiles non conventionnels, comme par exemple les schistes bitumineux, les sables asphaltiques et la lignite. Cette communication considère une transition des systèmes d'énergie actuels vers de nouveaux systèmes de conversion et de distribution d'énergie fossile qui maîtriseront tous les mouvements de masses et éviteront ainsi des émissions dangereuses pour l'environnement. Il est ensuite naturel de prolonger ces considérations vers la perspective d'un système d'énergie durable basé sur l'hydrogène et donc non soumis à une limitation de ressources.

1. INTRODUCTION

The Energy Systems Program Group of the International Institute for Applied Systems Analysis (IIASA) has conducted a seven-year study of the global energy problem. This work, described in a two-volume report entitled 'Energy in a Finite World',[1] identifies two internally consistent scenarios for the seven world regions. These indicate a possible transition by the year 2030, from the current reliance on relatively cheap, clean, and easily accessible fossil energy sources towards a more advanced, albeit not sustainable, energy system based on increasingly dirtier, harder to exploit and therefore costlier fossil energy sources.

During this transition, it is of fundamental importance to integrate various stages of energy conversion, transport, and distribution into a novel energy system having a flexible new infrastructure for the use of low-grade fossil resources. This must be done with the least adverse effect on the environment and on the comfort of the consumer. In this paper we will propose such a novel energy system. But first we will address the major findings of the global study, which indicates the necessity for the transition to such a system during the next decades.

2. ENERGY SUBSTITUTION DYNAMICS

In order to encompass fundamental changes in the energy system, the study's quantitative and detailed analysis of energy demand and supply in the two global scenarios spans 50 years. By interpreting energy forms as commodities competing for a market, Marchetti and Nakicenovic[2] have shown the remarkable regularity of these changes, expressed as substitution of new for old energy forms. Figure 1 shows the primary energy substitution in the world during

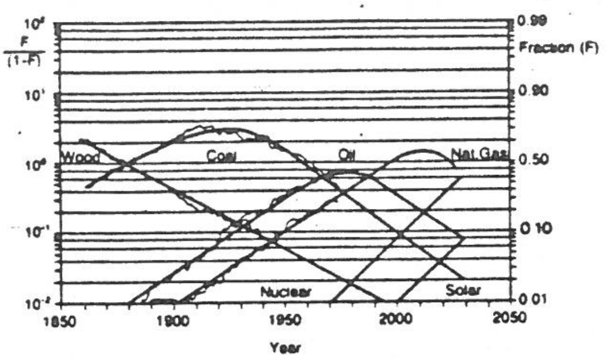


Fig. 1. Primary energy substitution in the world, 1860–2030.

the last 120 years and highlights the slow historical shift from fuel wood via coal to today's main energy sources, crude oil and natural gas. The regularity of this substitution process is revealed in Fig. 1, where the market shares of each energy source are logarithmically transformed so that logistic transitions appear as straight lines.

It is striking that the regularity of these changes has not been disrupted even by the two world wars or the two economic depressions. Given these regularities, the data can be extrapolated beyond 1980 to reveal a peaking and subsequent decline of the share of oil, and an increasing share of natural gas in the decades to come.

Figure 1 also shows that a new energy source must capture at least a few percent of the market share before it can successfully compete with established energy sources. Nuclear energy is in such a position today and, if it proves to be successful, would need at least 50 years, according to the analysis, to provide 30% of primary energy. Solar energy, if it should exceed a few percent share at all, would capture less than 10% of the share by 2030. Assuming a combined market share of less than 40% for these two sustainable energy sources by the year 2030, and realizing that total energy demand will increase in the decades ahead, one can readily conclude that greater volumes of fossil fuel will be needed in the future.

3. ENERGY DEMAND AND CONSUMPTION

The logistic substitution analysis indicates that the global energy system is characterized by long lead times. Hence, a 50 year time horizon was chosen for the global study. Its two global scenarios balance energy demand and supply for the seven world regions over this 50 year time horizon but these scenarios are based on a different methodological approach. The scenarios are labelled High and Low, the former referring to a global situation in which primary energy demand is relatively high but still manageable by 2030, with a 4.3-fold increase over the 1975 level, and the latter referring to a situation in which demand is relatively low, with a 2.7-fold increase. The two IIASA scenarios have been frequently referred to since their publication. The Low Scenario is often considered to be more realistic as to likely increases in primary energy use, although it does not always meet the expectations of the developing world. Recently, Runge *et al.*,[3] considered the Low Scenario as a realistic upper limit on future primary energy consumption.

Aggregate final energy* demand envisaged for the seven world regions reflects the substantial energy savings that result from structural changes throughout the economy, assumed conservation measures, and increased energy use efficiencies. When these factors are incorporated into the global energy study, it shows that final energy intensity (final energy to GDP ratio) reductions of up to 50%† could be achieved in the two scenarios. Such reductions are possible even though energy intensity is initially expected to increase in developing countries, due to the expansion of their industrial base and economic infrastructure.

Table I gives the aggregate final energy demand for the two scenarios and the relative share of liquid fuels and electricity in total demand. It indicates a fundamental need in both scenarios for a continuous liquid fuels supply, in spite of the attempt to conserve liquid fuels for premium uses (motor fuels and feedstocks for petrochemical products). Conservation of liquid fuels increases the need for other final energy forms including electricity and district heat. This all points to the fact that an adequate supply of liquid fuels will remain both a focal point and a primary concern in any future energy supply system.

4. ENERGY RESOURCES AND SUPPLY

The assessment of the resource potentials for coal, oil, natural gas, uranium, and renewable energy resources such as biomass was an important aspect of the global study. It was also a prerequisite for a consistent balancing of demand and supply in various world regions. In this context, recoverable coal, oil and gas resources are of primary interest.

* Here it is crucial to distinguish between primary and final energy. The former refers only to the resource consumption, such as fossil fuels or natural uranium, the latter to energy forms that are directly demanded, such as gasoline or electricity.

† Average global final energy to GDP ratio is roughly 1 (kWyr/yr per $(1975) GDP *per capita*).

TABLE I

Electricity and liquid fuels share in final energy in the world, high and low global scenario, 1975 and 2030

	Base Year 1975	High Scenario 2030	Low Scenario 2030
OECD Countries			
Final energy in TWyr/yr (10^{20}J)	3.5 (1.1)	8.0 (2.5)	5.6 (1.8)
Electricity in %	12	21	21
Liquids in %	56	46	46
Motor Fuel and Feedstocks % of the Liquids	63	90	83
Soviet Union and Eastern Europe			
Final energy in TWyr/yr (10^{20}J)	1.3 (0.4)	3.7 (1.2)	2.6 (0.8)
Electricity in %	10	23	20
Liquids in %	34	32	30
Motor Fuel and Feedstocks % of the Liquids	65	100	100
Latin America, Africa and Asia			
Final energy in TWyr/yr (10^{20}J)	1.0 (0.3)	10.6 (3.3)	6.0 (1.9)
Electricity in %	6	13	13
Liquids in %	48	50	54
Motor Fuel and Feedstocks % of the Liquids	66	91	89
World			
Final energy in TWyr/yr (10^{20}J)	5.7 (1.8)	22.8 (7.2)	14.6 (4.6)
Electricity in %	14	17	17
Liquids in %	50	45	46
Motor Fuel and Feedstocks % of the Liquids	64	92	88

Source: 1

Table II details the respective conventional and unconventional resource estimates.

Not surprisingly, roughly one half of the world's conventional resources, or about $100 \cdot 10^9$ toe/yr ($41.6 \cdot 10^{20}$ J/yr), are concentrated in the Persian Gulf area. This resource distribution changes dramatically when unconventional oil resources are also considered. Potentially, in terms of energy content, there are at least four additional 'Persian Gulfs': the Athabasca deposit in Canada, Colorado in the United States, the Orinoco in Venezuela, and the Olenek Siberian deposits of the Soviet Union. However, the oil resources of these 'additional Gulfs' are not only environmentally dirtier and more expensive to exploit, but, more importantly, they are not in liquid form.

Coal resources are very large, exceeding combined crude oil and natural gas resources. Coal is also unevenly distributed. The lion's share of the total is concentrated in North America and the Soviet Union. Natural gas resources are more evenly distributed among the world regions. But these resources, particularly the unconventional ones, are not as well

TABLE II

Ultimately recoverable fossil resources of the world in 10^{20} J (10^9 toe)

Resources	Coal		Oil			Gas		
Cost Categories[a)]	1	2	1	2	3	1	2	3
North America (USA and Canada)	54.8	73.0	7.2	8.2	39.4	10.7	12.6	9.1
Soviet Union and Eastern Europe	42.8	141.1	11.7	14.2	21.7	20.8	16.0	9.7
Western Europe, Japan, Australia, New Zealand, South Africa, Israel	29.3	46.6	5.4	1.0	6.6	6.0	1.6	4.4
Latin America	3.2	3.4	6.0	25.5	34.6	5.4	3.8	4.4
Africa (except Northern Africa and South Africa) South and Southeast Asia	17.4	16.4	7.9	1.6	10.4	5.1	3.1	4.4
Middle East and Northern Africa	0.3	0.3	41.6	8.5	–	34.0	3.1	4.4
China and Centrally Planned Asian Economies	29.0	39.1	3.4	4.1	4.7	2.2	4.1	4.4
World	176.3 (394.5)	320.9 (717.9)	83.1 (186.0)	63.0 (140.9)	117.5 (262.8)	84.1 (188.1)	44.4 (99.3)	40.9 (91.6)

a) Cost categories represent estimates of costs either at or below the stated volume of recoverable resources (in constant 1975 $)

Coal: Category 1: $ 25/ton; Category 2: $ 25 to 50/ton

Oil, Gas: Category 1: $ 12/barrel; Category 2: $ 12 to 20/barrel; Category 3: $ 20 to 25/barrel

Note: Numbers in columns may not add to world totals due to round-off errors.

Source: /1/

documented or searched for as those of oil and coal. However, recent advances in deep drilling technology, as well as in gas conversion to more easily transportable energy forms (say, methanol), raise the possibilities of both enhanced availability and unprecedented use of gas resources. As a result, the Energy Group at IIASA recently began a reevaluation of gas resources and their future role.

The various stages of energy conversion, transportation, and distribution separate energy resources from final energy demand. Each scenario assumes the implementation of a minimum cost energy system, capable of delivering the energy demanded from available resources under the constraints on buildup rates of new technologies and so on. By 2030, the final energy demands of 22.8 TWyr/yr ($7.2 \cdot 10^{20}$ J/yr) in the High and 14.6 TWyr/yr ($4.6 \cdot 10^{20}$ J/yr) in the Low Scenario (see Table I) result in primary energy requirements of $25.1 \cdot 10^{9}$ toe/yr ($11.3 \cdot 10^{20}$ J/yr) and $15.8 \cdot 10^{9}$ toe/yr ($7.1 \cdot 10^{20}$ J/yr) respectively.

Both scenarios revealed that the feasibility region was very limited, with the most dominant constraints being the availability of time and capital. The narrow feasibility region also meant that all available energy sources had to be used: there are no alternative energy sources, and the scenarios are feasible only if all energy sources are harnessed.

Let us now consider briefly how the primary energy requirements are met by different energy sources. The emerging pattern confirms the dominant role that hydrocarbons will continue to play in the future. Increases in coal usage are especially large, followed by rising gas utilization. A continuing, strong dependence on oil is assured in both scenarios, however, by steady increases in oil consumption.

We will now examine the reasons that led to this increased coal usage, since it appears to contradict the logistic substitution analysis. In terms of relative shares, the use of oil drops globally from about 44% in 1975 to almost 19% by 2030 in the High Scenario. This is possible, despite inelastic demand for liquids, because synthetic fuels produced by autothermal liquefaction of coal provides a substitute for oil. This also explains the relatively high consumption of coal, and stresses the principal role of liquid hydrocarbon fuels in the future.

A more widespread use of natural gas was not considered possible in the scenarios, since transporting it over intercontinental distances was assumed to be uneconomic. The Energy Group at IIASA, however, is currently considering a new scenario where natural gas is treated as a truly global commodity. This scenario would become even more important if it should turn out that the OPEC oil export ceiling is less than the assumed $1.7 \cdot 10^{9}$ toe/yr ($0.1 \cdot 10^{20}$ J/yr). Moreover, in the new scenario, natural gas should satisfy some of the demand that would otherwise be met by coal, which plays a swing role in the two global scenarios.

The high demand for synthetic fuels will not only cause tremendous coal supply problems, but also equally large waste disposal and CO_2 problems. This indicates the need for allothermal coal gasification or liquefaction whereby coal serves only as a source of carbon atoms and does not remain simply as a source of energy. In order to relieve the strained coal supply, nuclear energy, including breeder reactors, will be devoted exclusively to electricity generation. The nuclear share of about 23% of all primary energy in the two scenarios is significant, but it is lower than indicated by the logistic substitution analysis explained above.

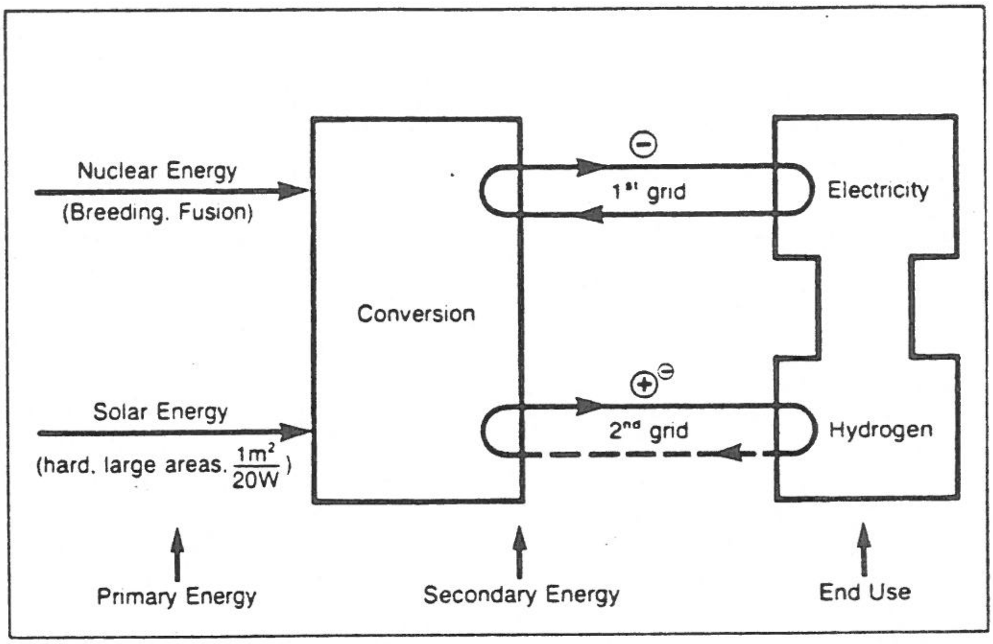
5. SUSTAINABLE ENERGY SYSTEMS

Thus, the year 2030 will see only the beginning of a sustainable energy system. Until then, there will be an enhanced use of fossil energy. Although there are problems associated with the use of difficult and dirty fossil resources, there are also novel opportunities that could ensure a smooth transition to the nonfossil, sustainable energy systems of the future. Hydrogen is a key component of such a strategy for reasons that become evident when we consider the features of a sustainable energy system.

On the primary side, a sustainable energy system must not rely on the consumption of resources. Currently, this limits the possibilities to solar and nuclear power. Nuclear power is virtually decoupled from the use of scarce resources when it is based on the principle of breeding, be it by the use of fast breeder reactors, thermal breeders or D-T fusion machines. In terms of its energy content, 1 g of nuclear material then becomes equivalent to $3 \cdot 10^{6}$ g of carbon in fossil fuels.

Nuclear and solar energy cannot be used directly and therefore must be converted into clean secondary energy forms. Electricity is not expected to do the job alone since it is difficult to store and transport over large distances. Hydrogen is the best candidate to complement electricity and in that way replace the hydrocarbons of today.

Electricity could not have become as useful as it is in the absence of electricity grids. Grids integrate many small end-users, eliminate consumer storage



However, large investments of capital ($\frac{\$ 10000}{cap.}$), labor, and resources, e.g. $\frac{50 kg}{m^2}$ are required

Fig. 2. Unlimited energy from a sustainable energy system without consumption of resources.

needs, and thus permit the benefits of economies-of-scale. Today's network for the distribution of liquid and gaseous fuels offers many of the same advantages to the final consumer. Thus, one could speak of the existence of a 'second grid'.

Hydrogen can be stored and transported over large distances, and could consequently provide all the services of the second grid. Figure 2 indicates this point, but unfortunately it also indicates that such a sustainable energy system would be very capital intensive. For example, a 3 kWyr/yr (10^{11} J/yr) per capita energy consumption level and an average systems cost of 3300 \$/kW installed implies a capital stock need of 10 000 *per capita* just for energy purposes. Today, the average capital stock in the world is about 2000 *per capita* and only about 600 of this is for energy purposes. Therefore, a sustainable energy system essentially necessitates a 16-fold increase in the average capital stock *per capita*. At an annual growth rate of 3% above the rate of population growth, this implies that the evolution of a sustainable energy system will take roughly 100 years. At lower growth rates, even more time would be needed. In other words, sustainable energy systems could hardly be expected before the year 2100. A logistic substitution analysis leads to the same conclusion.

If hydrogen will only gradually replace the carbon atom in the hydrocarbons, the sustainable energy system of the future must be approached gradually via an intermediate and novel fossil energy system. Hence, it is only natural to consider the hydrogen to carbon (H/C) ratio in its evolution during the last

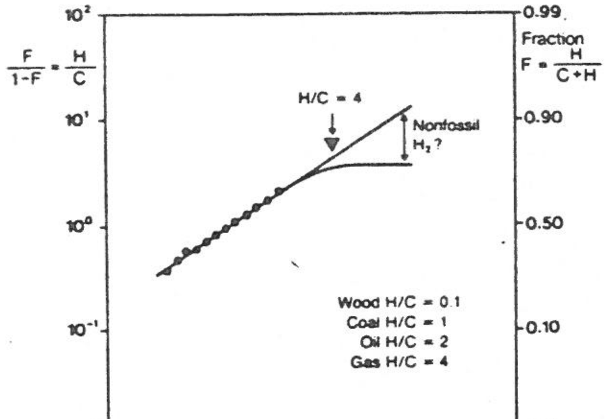


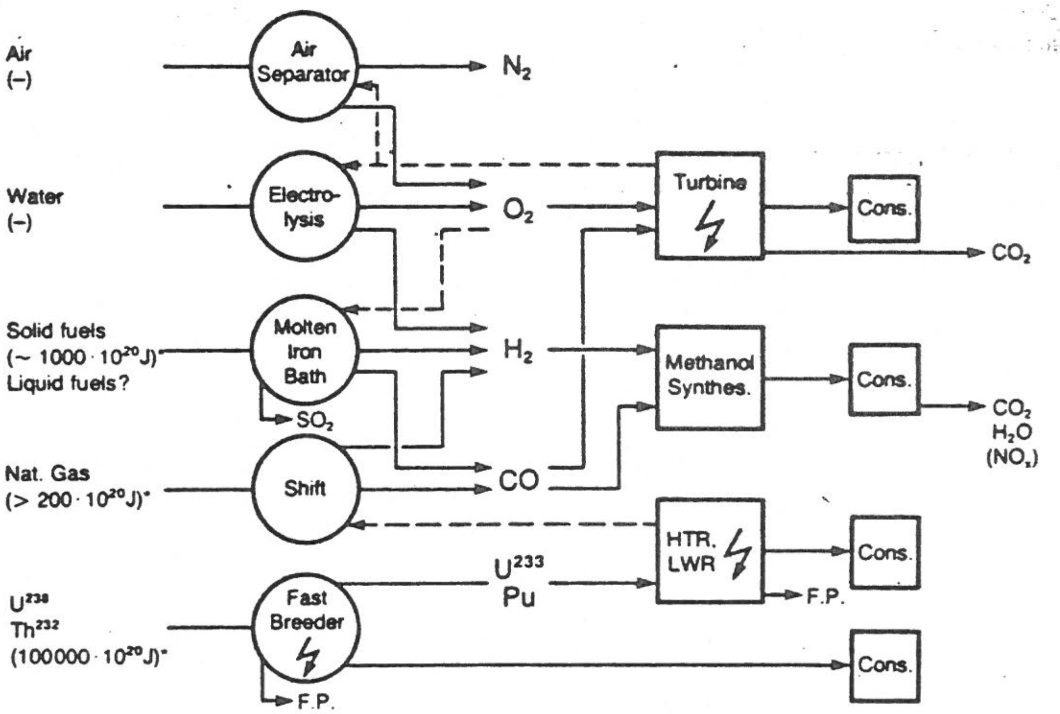
Fig. 3. Hydrogen to carbon ratio (H/C) of fossil fuels in the world, 1860–2100.

In the case of the fourth energy chain, that of nuclear power, a further conversion step, fuel conditioning, is inserted into the chain. Fuel conditioning implies chemical conversions of uranium ores and isotopic enrichment. At the power station fission products are generated, the analog to the emissions from combustion of fossil fuels, but fission products are mostly contained and not released to the atmosphere.

These energy chains are interconnected only insofar as electricity supply is concerned. In this case, energy substitution is possible before the consumer is reached. In all other cases, however, substitution can only take place at the point of consumption, for instance by switching from an oil to a gas burner in a dwelling. Therefore, the demand for liquid hydrocarbons, described earlier as critical and difficult to satisfy, is directly coupled to the supply of a liquid primary energy source, crude oil. This is a far-reaching observation. It partly explains the seriousness of the past oil shocks, because it is only down at the consumer end that these shocks can eventually be absorbed.

Let us now consider the new approach to a second generation integrated energy system. The idea is to contain mass flows and integrate the energy chains that connect primary fuels with the end uses. Containing mass flows means avoiding use of the atmosphe.e as a dumping ground for spent fossil fuel and related side streams. In principle, this means zero emissions and a complete containment of mass flows, although in practice there will always be technical losses. A pipeline is in that sense a possible zero-emission scheme. This is in contrast to schemes, like stack gas cleaning, that can technically approximate zero emissions but cannot in principle achieve them.

Spent fossil fuel is a mixture of CO_2 and H_2O, the oxidation forms of the two competing fuel components (H and C) that were considered above. As mentioned before, H_2O is environmentally harmless while CO_2 is a potential long range problem. It is not a problem, however, that would arise in the next ten or twenty years. Consequently, while the dangers must be kept in mind, they are not of the highest priority. Instead, the highest priority must be given to the avoidance of NO_X and SO_2 emissions. These originate from the combustion of solid fuels with air. The urgency of the related environmental problems is highlighted by the acid rain problem.



*these numbers reflect perception of resources as seen since the early eighties

Fig. 5. Mass flows in novel fossil energy systems.

century. Marchetti[4] considered this evolution in the spirit of a logistic substitution process by designating the ratio of the market share held as hydrogen (f) over the market share held as carbon (1-f). Recalling that the H/C ratios of fuel wood, coal, oil, and gas are roughly 0.1, 1, 2, and 4 respectively, Fig. 3 indicates that the H/C value of 4 would be reached by the year 2000. Beyond the year 2000, the H/C values shown in excess of 4 imply the generation of exogenous hydrogen from non-fossil sources, and thus the advent of the sustainable energy systems. The complete substitution of hydrocarbons by hydrogen should not be expected before the year 2100. It is reassuring to arrive at this same conclusion by following an alternative route.

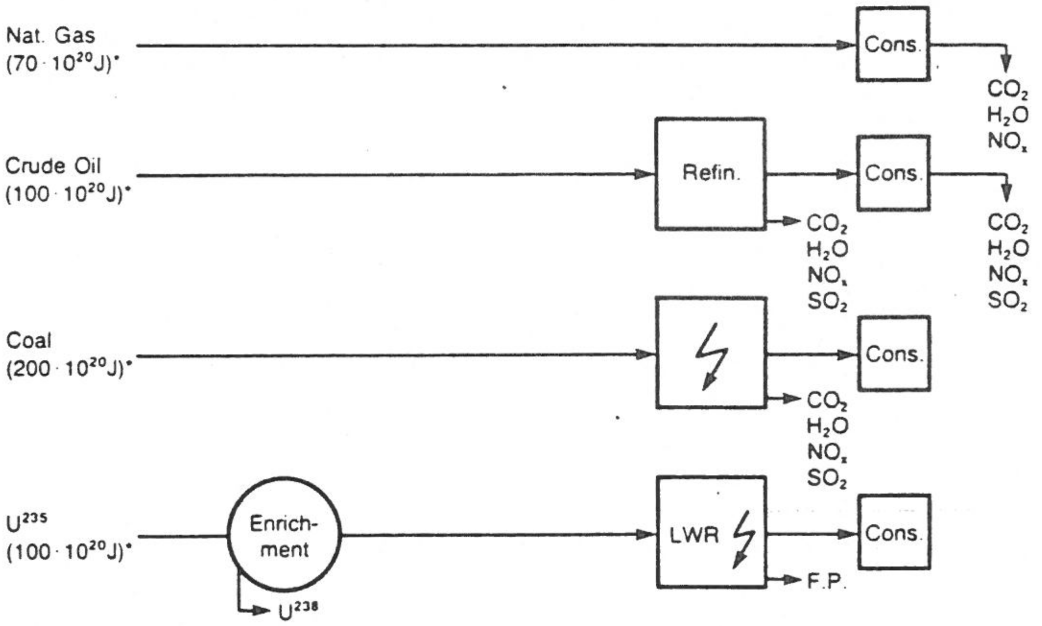
6. NOVEL ENERGY SYSTEMS WITH CONTAINED MASS FLOW

During the transition from the current energy system to sustainable systems of the far future, a novel energy system is needed which exploits low grade fossil resources without harming the environment. The approach described herein is based on the idea of closing the mass flows of fossil materials in such a way as to allow a smooth transition to the hydrogen-oriented, second grid of the sustainable energy system by continuous increases on the overall H/C ratio. E. Schmidt (New York) has referred to this intermediate energy system as the second fossil and nuclear age, the current energy system being the first fossil and nuclear age. In order to understand the main features of this new energy system we must first describe the current energy system in appropriate mass flow terminology.

In the current energy system, shown in Fig. 4, conventional gas is delivered directly from the source to the consumer. At the location of the consumer, CO_2, H_2O and NO_X are produced and released to the atmosphere upon usage. H_2O is of no environmental concern. CO_2 is a potential long range global concern, and NO_X is one of serious regional concern.

The second energy delivery chain, that of oil, does not lead directly to the consumer. A conversion station, the refinery, is inserted before the consumer. At the location of the consumer, there are again emissions into the atmosphere of CO_2, H_2O, and NO_X, but this case also entails emissions of SO_2. There are emissions at the refinery as well, for which the refinery is responsible.

The third energy chain, that of coal, is essentially used for the generation of electricity, so that all the environmental responsibility goes to the electrical power plant responsible for emissions to the atmosphere. The consumer thereby becomes environmentally clean. The fossil fuel cycle is considered to be open, since the spent fuel products, CO_2 and all other side streams, are released into the atmosphere.



*these numbers reflect perception of resources as seen until the early seventies

Fig. 4. Mass flows in current energy systems.

The basic idea behind containing mass flows is simple: it is to apply the concept of nuclear fuel conditioning to fossil fuels by decomposing them. This implies the early elimination of side streams and thus cleaning prior to combustion. This idea is captured in Fig. 5.

Let us start with the decomposition of air. This means the separation of nitrogen from oxygen and hence the elimination of about two thirds of the NO_X emissions of today's open cycle combustion. The other third of NO_X emissions is due to the nitrogen content of solid fuels and will be addressed below. Such separation of air implies stoichiometric burning of the fossil fuels, which requires technical adaptations or improvements of existing technologies. It also implies reducing related gas flows to 20% so that capturing the product of such combustion, CO_2, becomes conceivable, should this eventually become necessary.

As a next step let us consider the decomposition of solid fuels, be it bituminous coal, lignite, shale oil or tar sands. The molten iron bath, under development in the FRG by the firm Humboldt-Wedag, is an example of a technology suited for such decomposition. In this scheme particles of the solid fuel are introduced into a vessel containing molten iron. At 1400 °C any chemistry is broken. When oxygen is added stoichiometrically, a mixture of carbon monoxide, hydrogen, and traces of sulphur dioxide (less than 20 ppm) is liberated from the fuel. The nitrogen content of the fuel is also released and undergoes chemical reaction. The salient point is that all the ashes, including practically all of their environmentally hazardous sulphur and heavy metals content, form a slag on the surface of the iron bath. This slag can be easily removed, thus eliminating the flow of environmentally poisonous mass streams at the front end of the fossil fuel cycle. As already mentioned, the SO_2 content of the product gas would be as low as 20 ppm and completely satisfactory environmentally. Further, since practical applications of the product gas necessitate further treatment, the residual SO_2 component could also be removed.

It should be reiterated that, by closing the environmentally hazardous mass streams, the heavy metal content of the fuels is contained as well. As the sensitivity for impacts becomes larger, as in the case of the acid rain, the potential impacts of these heavy metals become larger. The scientific and general publics are only beginning to comprehend the dimension of the environmental threat associated with the use of low grade fossil fuels.

Appropriate technologies for the decomposition of crude oil must also be examined. The molten iron bath is only *one* option, and there are certainly others. In principle, the case of future crude oil uses parallels that of the solid fuels. But we refrain here from a review of the related technical options.

The decomposition of solids yields a product gas that is poor in hydrogen. If this gas is to be converted into gasoline or methanol, its hydrogen to carbon ratio must be increased to two by exogenous hydrogen. Steam reforming of natural gas could provide the necessary hydrogen not only because natural gas has a hydrogen to carbon ratio of four, but also because the shift reaction leads to the splitting of the water molecules that are present. Usually this is done autothermally, that is three to four carbon atoms are engaged to put one carbon atom into the product of the reaction. However, in view of the long range necessity of controlling CO_2 as well, it seems prudent and appropriate to consider allothermal schemes. The provision of high temperature process heat could be provided, for example, by high temperature nuclear reactors or, in more sunnier parts of the world, from solar power towers. The former possibility is being actively pursued at the Kernforschungsanlage Jülich (KFA) in the FRG where a 10 MW demonstration plant (EVA II) has been successfully operating for a year. The latter possibility is being pursued at the Weizmann Institute of Israel in conjunction with KFA.

A considerable degree of freedom is to be gained by additional water decomposition, because the products will not always match stoichiometric constraints. Water decomposition can be done by modern electrolytic schemes, although thermochemical schemes should be considered as well.

Finally, it should be observed that the nuclear Fast Breeder Reactor (FBR) fits this scheme of the second fossil and nuclear age too. The FBR can be considered as a fuel conditioner for the 'low grade' nuclear material, because it converts truly plentiful U^{238} and Th^{232} into nuclear material which is directly fissionable. The fissionable material produced in the radial blanket of the FBR can be used to feed either normal Light Water Reactors or High Temperature Reactors. It should be borne in mind that the sustainable energy system of the future is expected to rely to a large extent on the operation of the FBR.

The principal product of the decomposition of fossil fuels would be clean carbon monoxide, oxygen and hydrogen. These energy forms are neither primary nor, in the normal sense of the word, secondary energy forms. They are clean intermediate energy forms. Since the desired secondary energies continue to be electricity and (liquid) hydrocarbons,* it is natural to consider conversion facilities for the synthesis of methanol or gasoline and for the generation of electricity. These conversion facilities should be seen as elements of the proposed integrated energy system. For example, if carbon monoxide and oxygen are available as energy sources, it seems possible to use high temperature turbines that operate with isothermal expansion of CO and O_2, thus yielding thermal efficiencies of more than 60%.[5] This, among other things, can help to overcome energy requirements of the air separators and electrolyzers. Other advanced schemes for the synthesis of methanol and gasoline, such as Fischer Tropsch and Mobil Oil methods, should also be reviewed for possible application within the novel fossil energy system.

The integration of the steps we have considered results in considerable flexibility and improvement of the whole system. Such integration is therefore the other aspect of the novel fossil energy system. The intermediate energy forms allow for two sources of oxygen (air separation and electrolysis), three sources for hydrogen (electrolysis, molten iron bath and the shift reaction) and two sources for carbon monoxide (molten iron bath and the shift reaction). It therefore permits interfuel substitution much earlier than at the point of end use. This adds flexibility and permits a smooth adaptation to the expected evolution of the H/C ratio. Such early interfuel substitution should be accomplished by an appropriate grid, incorporating or substituting for costly and inflexible district heating systems which now transport heat at high costs over insufficient distances, instead of carrying intermediate energy forms at low temperatures.

Further work is required on integrated fossil energy systems with contained mass flows. At the systems level, formal allocation algorithms must be applied to structure various components into an interconnected and flexible infrastructure. A mixed-integer programming approach could be used to allocate individual facilities and respective mass flows within the system, and to integrate end use devices with the production of clean intermediate fuels such as O_2, H_2 and CO. Against this research at the systems level, a reassessment of the technologies that have been discussed is required. While all of these technologies exist, they were developed for different kinds of use. Applications on the scale of hundreds of gigawatts were not originally envisaged. This is true not only for more common technologies such as electrolysis but also for the molten iron bath scheme, etc. In the case of the High Temperature Reactor, further development work is necessary, since the reactor is indeed capable of heating helium to 950 °C in the ceramic nuclear core. But there are still great difficulties in containing 950 °C helium in metallic environments, and metals will continue to be necessary for heat exchanging devices, at least for some time to come. KFA in the FRG therefore envisages the construction of a small 50 MW_{th} experimental reactor called AVR II. In this reactor, the high temperature alloys of the heat exchanging devices should be experimented with rather than the nuclear core. Together with the EVA II facility, which is already in operation, this could provide a powerful testing ground for the second generation uses of fossil fuels.

KFA is working intensely on these novel fossil energy systems. It closely cooperates with the Energy Laboratory of the Massachusetts Institute of Technology with IIASA and with the University of Umea and the City of Stockholm in Sweden. This is not a closed club.

7. OUTLOOK

Quantitative scenarios are necessary to sharpen reasoning and deepen insight but they can do no more than to describe a qualitative situation. Since situations are constantly changing, continuing review is necessary. We must have a clear understanding about future directions as well as perspective on the likely timing of events because the adaptation and evolution of the energy system's infrastructure takes time.

Accordingly, the reasoning presented here implicitly assumes that evolution will be smooth and therefore could be represented by a smooth trajectory in a phase space. Recent progress in the field of nonlinear dynamics, however, has again taught us that transitions are not always smooth: there is also chaotic or turbulent behaviour. Indeed, Marchetti's substitution analysis, for instance, indicates deviations from the straight lines of his logistic evolution trend. They last for a decade or so but eventually the long trend prevails. Obviously, in the eighties we have entered such a decade of turbulence and there are many phenomena which, at least for the time being, appear to contradict the picture presented here. These phenomena are serious and can mean death or survival for many industries. In a storm, when only a a good ship can survive, smooth sailing is a later

* The use of hydrocarbons by the end user would result in the generation of some NO_x. Only the eventual replacement of carbon by hydrogen can prevent this.

concern. Therefore, these short range difficulties must be taken very seriously, and good analysis is necessary to guide us through the turbulence. But this was not the goal of the long range and global perspective. It may be of some help, even in the eighties, to have an idea of long range transitions. And clearly, a transition to gas and exogenously produced hydrogen does imply major changes in the present energy system. It also means that the nature of the contribution of oil and gas will change.

We would be well advised to gain a better understanding of these prospective changes. The oil and gas industries must avoid difficulties in the eighties that were so typical of the electrical industry in the seventies. And this might require a hard look not only at technology and systems analysis but also at investment decisions. Fundamentally, the overall situation is not bad. It is possible to arrive at novel fossil and eventually sustainable energy systems.

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