Solarzeitalter-Serie: „Vollversorgung der Gesellschaft mit Erneuerbaren Energien“

In Solarzeitalter 3/2000 hat Harry Lehmann das „Solare Energieversorgungskonzept für Europa“ vorgestellt - die Zusammenfassung einer Langzeitstudie unter Federführung des Wuppertal-Instituts für die EU-Kommission. Darin wird die Möglichkeit einer nahezu hundertprozentigen Energieversorgung der EU aus Erneuerbaren Energien bis 2050 aufgezeigt. In Solarzeitalter 4/2000 wurde ein 100 %-Szenario für Frankreich dokumentiert, 1978 verfasst von der Wissenschaftler-Gruppe „Le Groupe de Bellevue“ in Paris. Wir setzen diese Serie fort mit der 1982 publizierten Studie des Internationalen Instituts für Angewandte Systemanalyse (IIASA) im österreichischen Laxenburg. Diese ist deshalb interessant, weil das Institut nicht dafür bekannt ist, vorzugsweise die Erneuerbaren Energien im Auge zu haben. Die Studie beschreibt zwei verschiedene Vollversorgungskonzepte mit Erneuerbaren Energien für Europa - ein „Hard Solar-“ und ein „Soft Solar-“ Szenario, also eines auf Groß- und eines auf dezentralen Technologien basierend.

Die IIASA-Studie für eine vollständige Energieversorgung Westeuropas mit Erneuerbaren Energien

N. Nakicenovic, S. Messner

ZUSAMMENFASSUNG

Die Studie beschreibt zwei verschiedene Vollversorgungskonzepte mit Erneuerbaren Energien für Europa bis zum Jahr 2100 - das eine mit zentralen Energiesystemen auf der Basis von solarem Wasserstoff als hauptsächlichem Energieträger (Hard Solar), das andere mit dezentralen Energieträgern auf der Basis konsequenter Energieeffizienzsteigerungen (Soft Solar). Die Bedeutung beider Szenarien liegt in der fundamentalen Umstrukturierung des gesamten Energiesystems, der ökonomischen Strukturen und des Lebensstils in Westeuropa, um das Ziel der Vollversorgung mit Erneuerbaren Energien zu erreichen. In den Tabellen 1a bis 1c sind die Szenarien für 2100 im Vergleich zu dem Ist-Zustand des Jahres 1975 im Überblick dargestellt.

Two scenarios consider exclusively solar futures - one is based on centralized solar technologies (the Hard Solar scenario), and the other on decentralized user-orientated solar technologies (the Soft Solar scenario). By the term ‘sustainable energy future‘ we mean that continued energy supply is assured from practically infinite energy sources, and not necessarily that import independence is achieved, though it may be desirable. In any case it implies a transition away from domestic and imported fossil energy sources. While scenarios lead to sustainable energy futures before the year 2100, which is the time horizon of the study, the Hard Solar scenario requires substantial imports of solar-produced hydrogen. In addition, scenarios require fossil energy imports during the transition period before the sustainable energy systems are fully implemented. The overall implications of each scenarios are that fundamental changes of the whole energy system, economic structure and lifestyles are necessary in order to achieve sustainable energy futures in Western Europe. However, the nature of the changes is different in each scenario.

THE TEMPORAL SCOPE

This study was conducted, among other reasons, because the IIASA Global Study (Energy Systems Program Group, 1981) showed that sustainable energy systems could not be achieved by 2030, but also showed that such systems are required in order to assure improvements and avoid stagnation in human welfare during the next century. In order to assure continued economic growth one of the prerequisites is the availability of energy. Thus, in order to allow for enough time to complete the transition away from fossil energy sources, the temporal frame of the study is longer than 100 years, or more than twice as long as that of the Global Study. This is a very long period, but enough time must pass to permit the fundamental infrastructural changes that are required in the scenarios.

BASIC ASSUMPTIONS

The future energy outlook for Western Europe depends on a multitude of interdependent factors - most important among these are economic development and population growth. Therefore, the future evolution of Gross Domestic Product (GDP) and population are the two basic assumptions in the scenarios. Population evolution is based on projections developed by Keyfitz (1979) that indicate that Western Europe would reach a stable population of 570 million people by the end of the next century.

During this period of over 100 years, South Europe would increase its share in Western European population from 55 % in 1975 to 63 %, while the shares of North and Central Europe would decline from 6 to 4 % and from 39 to 33 %, respectively.

The projection of the GDP evolution in the scenarios is based on the GDP growth in Western Europe as in the Low scenario of the IIASA Global Study. The growth rates are highest in South Europe and reflect a reduction of the differences in economic development within Western Europe. The GDP projection implies an average 1.6 % per year growth rate, which may appear to be a low figure. However, this growth rate should be viewed as a sustainable longterm trend, and should be compared with a much lower population growth rate of 0.3 % per year. On average it leads to a more than fivefold increase in GDP per capita levels by the end of the next century.

THE ANALYTICAL APPROACH

The scenarios are formulated so as to provide extreme alternatives for achieving a sustainable energy future in Western Europe. Both are based on practically infinite energy sources - solar insolation, and renewable energy forms. The Soft scenario relies mostly on local solar energy with few average transport needs while the Hard relies on remote solar generation with very large transport needs. The scenarios outline the limits to what is feasible from the viewpoint of the whole energy system's configuration. Feasibility constraints such as these are usually more stringent than mere resource limits in that they require consistency throughout the entire system from primary energy through various forms of energy conversion, transport and distribution stages all the way to useful energy. They also involve cost minimization of the whole system under the constraints of build-up rates of new technologies in addition to resource constraints. They are constructs designed to analyse the limiting factors when one particular sustainable energy option is utilized to the largest extent possible. Together, they test the extremes of physically possible, yet still internally consistent, sustainable energy systems.

ENERGY DEMAND AND USE

Two sets of assumptions were used to result in two different energy demand projections, a Higher and a Lower one, both of them based on the same population and GDP projections described above. The large differences between the two are due to different lifestyle changes and energy use efficiency improvements. That is, different energy demand patterns and levels, at the same GDP, are possible since the GDP Index will actually measure different things as the economic structure and lifestyles change over time. The typical basket of goods associated with the Lower demand projection will be different from that of the Higher demand. These different material needs associated with the same GDP (that is, economic activity) level are assessed in the MEDEE-2 model in physical terms and, in conjunction with energy use efficiency improvements and lifestyle changes, result in specific demands for energy.

Here it is crucial to distinguish between different forms of energy, particularly 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. Between these two forms of energy are the various parts of the energy system: energy conversion, transport and distribution. The final energy that is applied to actual enduses results in useful energy, for example low temperature heat for space conditioning or gasoline for motor car propulsion. Ultimately, useful energy results in energy services, such as a well heated room, or person-kilometres travelled by car.

The energy demand levels are assessed in the MEDEE-2 model for all sectors of the economy, for example industry, transport, households and services, and within each sector by demand category. For those demand categories where a number of final energy forms (usually each with a different efficiency) could provide a given service the demand levels are specified in terms of the required useful energy or energy services. Where only one specified form of final energy can provide the service, the demand levels are specified in terms of final energy, for example hydrocarbons for feedstocks in chemical industry. The energy supply model MESSAGE II then determines the structure of an energy supply system that is capable of provi-

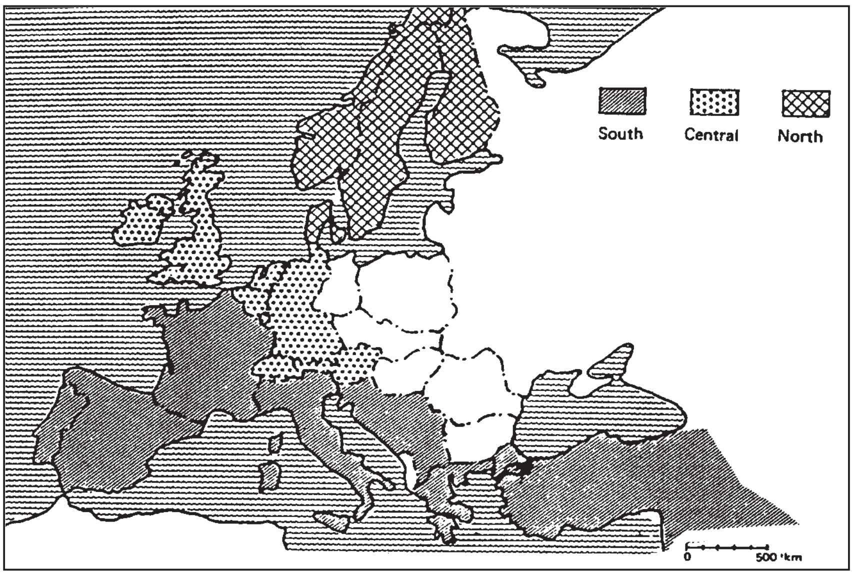

Figure 1: Western Europe

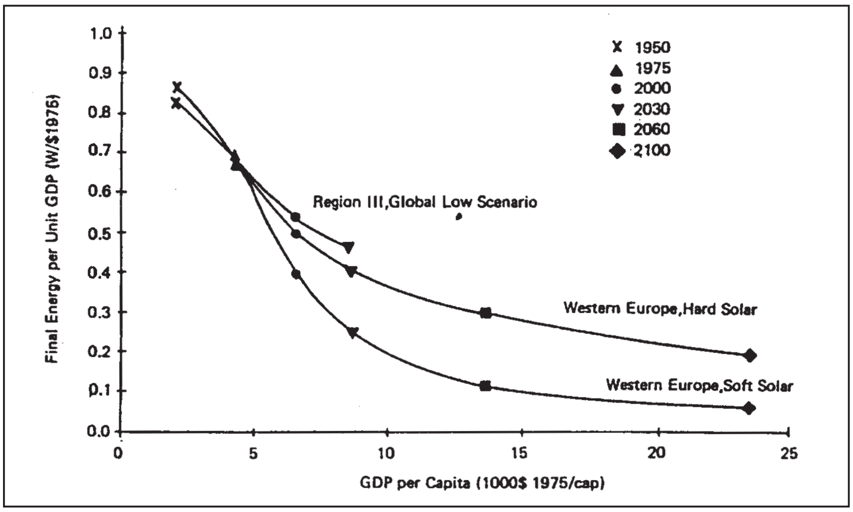

Figure 2: Energy intensiveness in the scenario

ding the demanded energy according to each specific use. The energy system configuration is specified by MESSAGE II so as to provide a cost minimal energy mix that meets demands under the constraints of maximal build-up rates for technologies and resource constraints. Thus, the dynamic balancing of energy demand and supply in each scenario can be divided into two parts: first, the assessment of energy demand level and the associated activities in the whole economy; second, the structure of the energy system capable of delivering the demanded energy to the consumer.

Starting from the energy system level closest to the consumer, the first energy balance that has to be fulfilled is that the delivered final energy must meet the demanded energy uses. Table 1 shows such a final energy balance in Western Europe for the base year of the study, 1975, and the final energy balances of the Hard and Soft Solar scenarios in the year 2100.

The first thing to observe is that exactly the same energy use categories are satisfied by final energy supply in the scenarios as in the base year. However, the structural shifts between today and the year 2100 go beyond substitution among solid, liquid, gaseous fuels and electricity and even beyond the substitutions of various forms of final energy within each of these categories; the actual use of final energy forms changes. For example, oil refinery products have a very widespread use today - as a source of heat (low and high temperature), as vehicle fuel and as feedstocks in the chemical industry (besides their use as a primary energy source in electricity generation). In the scenarios, methanol becomes the major liquid fuel, but its use is largely limited to feedstocks. As a major source of heat, oil products are replaced by many new forms of final energy; in the Hard Solar scenario hydrogen takes the central role and in the Soft Solar scenario the on-site generation systems (for example the roof-top solar collector). As an exclusive source of vehicle fuel, oil products are replaced mainly by hydrogen and electricity. Thus, the balancing of energy demand and supply in the scenarios results in a profound change of the energy system structure that leads to patterns of energy use different than today's.

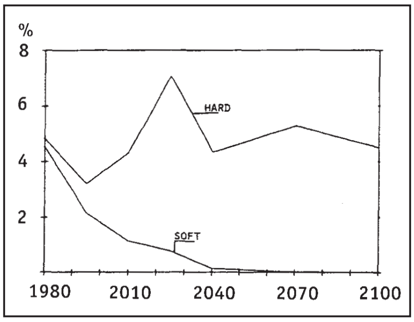

Figure 3: Cost of energy imports as share of GDP, Hard and Soft Solar scenarios

However, the structural changes are different in the two scenarios, and also the total amounts of final energy are different. In the Hard Solar scenario, the final energy more than doubles compared to the current final energy use, while it remains practically constant in the Soft Solar scenario during a period of more than 100 years. These relatively small increases in the final energy use in the Soft Solar scenario, and even the greater increases in the Hard scenario, illustrate the substantial energy efficiency improvements and overall conservation measures in the scenarios. Recalling that GDP grows more than sevenfold during the same period implies as a result extremely low final energy to GDP elasticities of 0.43 in the Hard and only 0.08 in the Soft Solar scenario compared with a historical elasticity of 0.79 (for the period 1950 to 1975). The aggregate energy efficiency improvements embodied in the scenarios are reflected in Figure 4 where final energy per unit GDP is plotted against GDP per capita for the two solar scenarios and, for comparison, the Low scenario of the Global Study. The overall energy use per unit of GDP is reduced by two-thirds in the Hard Solar scenario and by more than 80 % in the Soft Solar scenario (from 0.7 W per 1975 dollar in 1975 to 0.2 and 0.1 W per 1975 dollar in 2100, respectively). This could be achieved as a result of substantial changes throughout the economy and within each economic sector in addition to a change in lifestyles (such as reduced plane travel, user orientation in energy conversion) and enormous efficiency improvements of energy end-use technologies. Moreover, the energy use reductions were larger in the Soft Solar scenario than in the Hard scenario, the Soft Solar scenario being consistent with the Lower demand projection and the Hard Solar scenario with the Higher demand projection. Thus, although demand assessment in MEDEE-2 and the supply structure configuration of MESSAGE II can be viewed as two distinct steps in each scenario, the resultant balance, together with all of the constraints imposed in the analysis,

Final Energy Form	Final Energy Use: Thermal Low	Thermal High	Coke	Feed-stocks	Motor Fuels	Elec-tricity	Total
Coal	48.7	28.8	43.5				121.0
Oil Products	335.9	52.6		81.2	239.9		709.6
Natural Gas	109.1	86.7					195.8
Electricity						141.2	141.2
Biomass	26.4						26.4
Total	520.1	168.1	43.5	81.2	239.9	141.2	1194.0

Table 1A. Final Energy by Form and Use' Base Year 1975 (GWyr/yr)

Final Energy Form	Final Energy Use: Thermal Low	Thermal High	Steel-Production	Feed-stocks	Motor Fuels	Elec-tricity	Total
Coal			2.0				2.0
Electricity	68.2				31.6	644.0	743.8
Biomass	87.9						87.9
Methanol				518.0			518.0
Hydrogen	689.6	315.0	59.9		390.2		1454.7
Total	845.7	315.0	61.9	518.0	421.8	644.0	2806.4

Table 1B. Final Energy by Form and Use' Hard Solar Scenario, 2100 (GWyr/yr)

Final Energy Form	Final Energy Use: Thermal Low	Thermal High	Steel-Production	Feed-stocks	Motor Fuels	Elec-tricity	Cogene-ration	Total
Coal			1.0					1.0
Electricity	16.1	50.6			20.9	160.1		247.7
Biomass	13.8						96.2	110.0
Methanol				216.3				216.3
Hydrogen		1.7	31.2		173.5			206.4
District Heat	34.4							34.4
On-Site	344.7	70.5				156.5		571.7
Total	409.0	122.8	32..2	216.3	194.4	316.6	96.2	1387.5

Table 1 C. Final Energy by Form and Use, Soft Solar Scenario, 2100 (GWyr/yr)

represents the singular characteristic of a given scenario. The maximal possible reliance on decentralized solar and renewable energy Systems in the Soft Solar scenario, for example, leads to the Lower energy demand level. That is, Table 1 already indicated that in the Soft Solar scenario most of the demanded energy is supplied by small-scale solar or renewable sources using technologies located either at the site of end-use or as dose to it as possible. The collocation of energy generation and conversion systems dose to the user then imposes other overall constraints on the structure of energy demand and supply than do the centralized energy generation and conversion of the Hard Solar scenario with its long-distance energy transport and distribution requirements. In fact, the study shows that it is questionable whether decentralized energy generation, even when taken to the maximum degree possible, could at all be feasible with the Higher energy demand.

ENERGY CONVERSION AND SUPPLY

Table 2 shows the final energy supplies in the three scenarios by final energy form. All three scenarios lead to sustainable energy use by 2100. Fossil energy sources are eventually eliminated in all scenarios, but in 2030 the reliance on fossil energy supplies is still strong, a result that confirms the necessity of using a long time horizon of more than 100 years for the analysis of sustainable energy futures. However, in 2030 the relative use of fossil sources is the lowest in the Soft scenario and highest in the Hard Solar scenario. By 2100, the Soft Solar scenario relies mostly on on-site energy generation contributing 41 % of all final supplies. In addition, local energy sources such as district heat cogeneration and wind and photovoltaic plants contribute in the form of electricity 14 % of final energy compared to the total of 18 % of final energy delivered as electricity. The remaining electricity originates from hydropower. Only 15 % of all final energy is delivered in the form thermolytic hydrogen originating from large solar power plants in South Europe. Thus, the Soft Solar scenario is based on at most one-fifth of all final energy from large centralized energy generation systems.

In the Hard Solar scenario the opposite is the case. On-site energy generation is not used at all; 52 % of all final energy is delivered in the form of thermolytic hydrogen and 27 % as electricity. Both energy forms originate from large solar plants placed in sunny areas of the South and require long-distance transport and hydrogen storage. Thus, altogether in the Hard Solar scenario about 80 % of all final energy is delivered from centralized energy conversion technologies and in the Soft Solar scenario the same relative share is delivered from user-orientated, local or on-site systems.

In the Hard Solar scenario more hydrogen is delivered since it can also be used to store energy over longer periods in order to match the solar insolation availability and energy demand loads. In other words, about a quarter of all final energy should be in the form of hydrogen, about a quarter in the form of electricity, and a little less than a quarter is perfectly substitutable between hydrogen and electricity. This last category illustrates the flexibility that is given to the energy system and, most importantly, that the flexibility is limited to only 25 % of total final energy. In the Hard Solar scenario this flexibility was utilized as a buffer between energy supply and demand (in the form of hydrogen).

Table 2 shows hydrogen and electricity together provide almost 80 % of all final energy. In the Soft Solar scenario the same relative share of final energy is provided by user-orientated systems, but although the hydrogen and electricity (relative) use is redueed, it is still needed. This stresses again the importance of these two energy carriers in the future. The final energy deliveries that meet the demands result in primary energy requirements. In between are the various stages of energy conversion, storage in the case of hydrogen, transport and distribution. The final energy demands in the year 2100 of 1.4 TWyr/yr of the Soft Solar scenario and 2.8 TWyr/yr of the Hard Solar scenario result in primary energy requirements of 3.2 TWyr/yr, 5.8 TWyr/yr and 7.3 TWyr/yr, respectively. Table 3 shows how these primary energy requirements are distributed among different energy sources. Thus, from the structure of energy supply, the Soft Solar seenario is over 70 % ‘soft‘, and the Hard scenario relies more than 80% on eentralized solar conversion. Both scenarios rely exclusively on sustainable energy systems by the year 2100.

SUSTAINABLE ENERGY SYSTEMS

In each scenario the maximum feasible level of one type of energy supply system is used, which we refer to as the ‘reference system‘. In the Hard Solar scenario, the central solar power plants in South Europe comprise the ‘reference system‘. In the Soft Solar scenario, it consists of the loeal solar energy sources, such as the roof-top collector or the small neighbourhood wind or photovoltaic plant.

The whole structure of the energy supply system is determined by implementing the set of technologies which minimizes the overall cost of the supply system under constraints of build-up rates, resource depletion, etc. In order to use as much as possible of the specified ‘reference system‘ and still allow cost mimization, a cost penalty is levied on technologies which do not belong to the ‘reference system‘. The following cost penalty structure is used – 2.4 % per year cost increase of fossil resources, natural uranium and nuclear system investment costs. In addition, in the Soft Solar scenario, cost subsidies of 40 % for local and 60 % for on-site energy supply are actually awarded within the ‘reference system‘. We feel that such an approach leaves more flexibility to structure the energy supply system best

	Base Year	Scenario			
		Soft Solar		Hard Solar	
Form	1975	2030	2100	2030	2100
CoaI	10.1	4.6	0.1	14.5	0.1
OiI	59.5	6.6	0	15.2	0
Gas	16.4	4.2	0	21.8	0
Electricity	11.8	18.9	17.8	23.4	26.5
Biomass	2.2	9.8	7.9	5.3	3.1
Methanol	0	2.4	15.6	5.7	18.5
Hydrogen	0	13.5	14.9	14.1	51.8
District Heat	0	2.9	2.5	0	0
On-Site	0	37.1	41.2	0	0
Total(TWyr/yr)	1.19	1.17	1.39	1.82	2.81

Table 2. Final Energy Shares by Form, Soft and Hard Solar Scenarios, 1975 to 2100

suited under the given constraints.
Thus, the general approach is that all energy conversion, transportation and distribution technologies can compete to meet demands in both scenarios. We have assumed that technologies compete primarily on a cost basis, the cheapest technology available being used first. But there are constraints on the rates at which resources and potentials can be exploited, on the rate at which new facilities are built and implicitly on the total amount of any single activity that can be used. All of these numerous constraints affect decisions which would otherwise be dominated by cost considerations alone. Together with the differential cost changes they can be seen as deliberately forcing the energy system to maintain flexibility during the transition to a sustainable future — to provide diversity in order to cope better with unexpected changes. In fact, to the extent that the scenarios represent extreme future energy systems, they delimit the flexibility. For example, a future with lower energy use than in the Soft Solar scenario is perhaps possible, but within our analysis not by a smooth 'surprise-free' transition from the current energy system.

ENERGY IMPORTS

In 2030, during the transition period to sustainable energy supplies, all scenarios rely on fossil energy sources. Due to the lack of sufficient endogenous fossil sources in Western Europe most of these energy needs are balanced by energy imports. However, the relative shares of fossil energy sources are much lower even during the transition than today, so that import dependence is reduced in all scenarios by 2030. In 1975, 53 % of all primary energy consumed in Western Europe originated abroad. By 2030, only 2 % of all primary energy is imported in the Soft Solar scenario. A relative reduction of energy imports to 31 % of all primary energy is also achieved in the Hard Solar scenario. The reason for the relatively high import dependence of the Hard Solar scenario is that in addition to fossil energy imports most of the solar thermolytic hydrogen must be imported because the endogenous solar thermal potential of Western Europe is practically exhausted by electricity production. Moreover, after 2030 the energy import dependence increases again in the Hard Solar scenario due to increased hydrogen needs. In the other scenario energy imports are completely eliminated after 2060.

In the Hard Solar scenario it is assumed that hydrogen is imported from the Sahara since this is a sustainable source of energy, though of a non-European origin. Setting aside the political issues involved, we have assumed that the total production and investment cost of this scheme would be carried by Western Europe, so these costs are included in the scenario.

This observation offers an interesting comparison of the scenarios. The Hard Solar scenario was found to be compatible with the Higher energy demand projection. Perhaps the major single reason is that at the relatively high energy generation densities of the centralized solar conversion facilities (compared to those of the Soft Solar scenario) the energy supply is matched well with the demand patterns and levels of the Higher demand projection. The centralized supply system did not correspond with the Lower demand projection due to its high degree of implied energy conservation and user orientation. In the Hard Solar scenario this conservation and user orientation is simply not necessary, and, in particular, the high degree of user orientation of the Lower demand projection would have been uneconomical; it would require complex end-use technologies in addition to intricate and complex centralized energy conversion.

Thus, the drastic changes in the final and primary energy forms and their use and origin all indicate that the sustainable energy systems in 2100 are very different from the current one from the perspectives of both the user and energy supply infrastructure. lt is possible to observe some analogics to the current system as we have outlined above, but they stress even more the overall difference.

On the other hand, while these differences can hardly be overstated, the transition to these sustainahle energy systems takes on the order of 100 years, a long time indeed. Looking back 100 years or so, we would also encounter drastically different energy forms and use: fuelwood, some use of coal, animal muscle and wind power. All of these energy forms, except coal, can also be considered to be renewable. Thus, the transition foreseen in the scenarios appears to require changes of at least a comparable order of magnitude to those that took place during the last 100 years.

ENERGY IMPORT COSTS AND CAPITAL REQUIREMENTS

The infrastructural changes both in the energy systems and energy use in the scenarios imply not only different lifestyle patterns when compared with the current situation in Western Europe, but also changes in the structure of consumption and investments. In particular, the important questions are how the investments in the energy system and the payments for energy imports change over time. For Western Europe the transition to a sustainable supply of energy means that higher capital investments would replace the payments for the continuous imports of fossil energy.

By the year 2100 in the Soft Solar scenario, it would be possible for Western Europe to become selfsufficient and independent of energy imports. In the Hard Solar scenario such independence could not be achieved, but the results showed that energy imports would be reduced to solar hydrogen from the Sahara.

The capital for exploiting this resource would be provided by Western Europe. Thus, although not a Western European energy source, the hydrogen production in the Sahara was considered as a part of the capital requirements needed to implement the Hard Solar scenario. Thus, in the Hard Solar scenario,

Energy Source	Scenario				
	Base Year	Soft Solar		Hard Solar	
	1975	2030	2100	2030	2100
Coal	22.1	2.4	0	12.6	0
Oil	52.5	3.6	0	9.5	0
Gas	13.2	2.3	0	13.7	0
LWR	2.4	4.6	0	0.8	0
FBR	0	0	0	9.5	0
HTR	0	0	0	0	0
(Nuclear Total)	(2.4)	(4.6)	(0)	(10.3)	(0)
Hydropower	8.1	10.6	8.5	7.7	4.3
Biomass	1.7	8.4	15.1	10.1	9.4
Windpower	0	34.8	33.9	0	0
Wavepower	0	1.8	1.4	0	0
Photovoltaics	0	6.0	9.4	0	0
On-Site Sources	0	25.4	28.3	0	0
('Soft' Total)	(0)	(68.0)	(73.0)	(0)	(0)
Solar-Electric	0	0	0	19.9	3.4
Solar-Hydrogen	0	0.1	3.4	6.2	82.9
('Hard' Total)	(0)	(0.1)	(3.4)	(36.1)	(86.3)
Total(TWyr/yr)	1.53	2.36	3.16	3.2	5.76

Table 3. Primary Energy (Equivalent) Shares, Soft and Hard Solar Scenario' 1975 to 2100 (%)

Western Europe has the burdens of investing in the development of hydrogen production outside its borders, and of paying for continuous hydrogen imports. The cost of imported hydrogen was assumed to be the same as that of domestic hydrogen. Due to the fact that hydrogen production in the Sahara would be cheaper than in Western Europe, because of higher solar insolation and cheaper labour, the cost of imported hydrogen should leave enough room for some profit for the exporting countries.

This question of the cost of imported hydrogen gives a first glimpse that a realistic analysis of the economic impacts of the scenarios is extremely difficult, if it is possible at all. Most of these difficulties arise from the extremely long time horizon of the analysis. Precisely because the future price evolution is uncertain and not predictable over long time periods, all of the energy balances for the two scenarios were considered in physical units (for example primary or final energy equivalent) and not in terms of market prices. In addition, the costs of energy technologies and other components of the energy system were given in real monetary terms – in US dollars at 1975 prices and exchange rates. They express costprices of producing an energy commodity without accounting for future development of indirect taxes or other factors that determine market prices, such as individual utility preferences. Thus the cost figures used in the analyses are predetermined and were not based on market prices resulting from an economic equilibrium. In other words, the energy supply and demand balances were achieved by cost minimal allocation of energy to end-uses at given demands and not through a price mechanism. Only in such a way was it possible to structure an energy system capable of supplying sustainable forms of energy after a transition period of almost 100 years. But we must observe that just as our cost assumptions do not encompass short-term price variations, they are not predictions of long-term price developments either. In order to reflect financial flows in Western Europe correctly, a detailed world trade model would be needed to balance import requirements and export aspirations over long periods. However, such a model does not exist. Therefore we cannot analyse, even in a qualitative way, the possibility of increasing Western European export activities to the extent that they match energy import requirements. Thus we are not in position to evaluate the reasonableness of our GDP growth assumptions with respect to ability of the Wes-tern European economy to pay for the specified energy imports.

We can, however, compare the relative share of payments for energy imports in total GDP as shown in Figure 3. In the Hard Solar scenario the total energy import bill increases from less than 5 % in 1980 to a maximum of almost 7 % by 2025. The intermediate increase in the value of imported energy up to 2060 is caused by the need to import all of the required fossil energy. After 2060 fossil energy is completely phased out so that all of the imported energy by 2100 is in the form of hydrogen. For example, in 2030 73 % of the import bill is due to fossil energy imports and the remainder due to hydrogen imports from the Sahara.

In the Soft Solar scenario the energy import bill is very low. Already by 2030 less than 1 % of total GDP goes for energy imports, and by 2100 no energy is imported. This gradual decrease of the relative share of energy imports and eventual import independence in the Soft Solar scenario can only have positive effects on the total balance of payments and overall economic growth. However, even in the Hard Solar scenario the relative share of energy imports in GDP increases less than 50 % over a period of more than 50 years, and in the long run decreases below the current level. This should probably not cause any critical problems. It represents at most a doubling over the current energy import bills of most of the Western European countries (for example in the Federal Republic of Germany the share of energy imports in GDP was 3.1 % in 1975).

For reasons explained above it is unfortunately not possible to evaluate whether the energy imports of the Hard Solar scenario could lead to more serious economic problems, such as those involving balance of payment deficits, in the long-term future, though this appears unlikely in real terms. However, problems occur if payments for energy, foreign and domestic, clash with the increasing demands for highly capital intensive energy conversion and end-use technologies of the scenarios.

A trend parallel to such capital intensive infrastructural changes and the capital burden of virtual resource depletion is the growing consciousness of the environmental impacts of the energy system and all economic activities. Thus energy and other conservation measures along with the development of new infrastructures all add to the increase of capital requirements in the future.

Only some of these considerations are reflected in the high capital requirements of the scenarios. Figure 4 compares the total investments in the energy system for the Hard and Soft Solar scenarios. In the Hard Solar scenario the energy investment share in GDP increases to over 5 % in 2030 and gradually doubles by 2100. In the Soft Solar scenario it increases somewhat up to 2030 and slowly reduces to below 3 % of GDP by 2100. Thus, due to continuous economic growth, the energy investment share in GDP even in the Hard Solar scenario appears not to be too critical, though in absolute terms the energy investment requirements increase by a factor of 13 in the Hard Solar scenario and by a factor of 5 in the Soft Solar scenario. These total investments in the energy sector are based on the capital requirements of all technologies employed in the scenarios and differential cost changes that were described. Like all other cost assumptions in the scenarios, they are based at 1975 price levels and exchange rates in US dollars. In general, it should be observed that the capital requirements of energy supply and use in the two scenarios do not correspond directly to current accounting practices. Due to the increased complexity of energy end-use and strong user orientation in the Soft Solar scenario, the energy systems include all enduse devices and technologies and therefore also their costs. To ignore this part of the energy system would be to ignore the larger part of the energy supply, and the Soft Solar scenario especially would then appear to be misleadingly inexpensive without its large share of user-orientated technologies.

In both scenarios energy transportation and distribution capital requirements are comparatively low and their relative shares decrease as energy conversion and end-use become more complex during the next century. It should be observed that in the Hard Solar scenario central conversion capital requirements increase proportionally more than those of end-use. In the Soft Solar scenario the on-site energy technologies become the most capital intensive part of the energy system, accounting for almost a half of all capital requirements. Thus the structure of capital needs of the energy sector shows a different evolution in the two scenarios. In addition, the total capital needs of the Hard Solar scenario are three times larger than those of the Soft Solar. However, in the Hard Solar scenario the capital requirements include not only domestic investment but also the capital needs of solar generation of hydrogen in the Sahara. Presumably, such facilities would also be built by Western European companies, so that the adverse effects of foreign investments could be limited to purchases of raw materials abroad and the employment of foreign unskilled labour. These issues are very difficult and resemble somewhat those involved today in the decision to finance the development of natural gas pipelines in the Soviet Union in exchange for longer-term natural gas deliveries. The difference is not in the nature of the associated problems but only in orders of magnitude associated with a European venture of solar power development in North Africa.

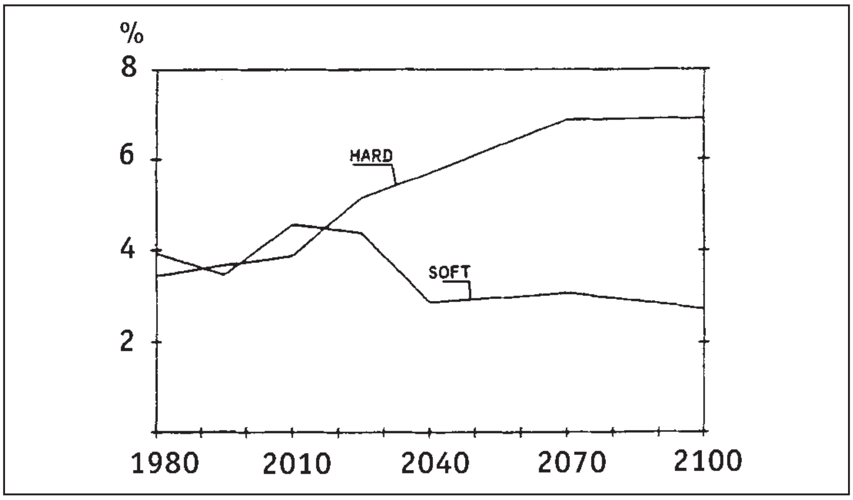

Figure 4: Capital Requirements as share of GDP, haed and soft solar scenarios