

WORKING PAPER

SOLAR ENERGY FUTURES IN A
WESTERN EUROPEAN CONTEXT

Executive Summary

N. Nakicenovic
S. Messner

December 1982
WP-82-126/a

Prepared for the Bundesministerium
für Forschung und Technologie of the
Federal Republic of Germany
Project ET 4359A

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PREFACE

The study considers three limiting scenarios that specify possible but not necessarily likely transitions to sustainable energy futures for Western Europe. Two scenarios consider exclusively solar futures--one based on centralized solar technologies (Hard scenario) and the other on decentralized, user-oriented technologies (Soft scenario). The third scenario, based on nuclear technologies, incorporates an intermediate degree of centralization in the energy system and serves as a comparison to the two exclusively solar scenarios. All three scenarios lead to sustainable energy futures before the year 2100, which is the time horizon of the study. While all three scenarios eliminate Western Europe's dependence on domestic and foreign fossil energy sources, the Hard Solar scenario requires substantial imports of solar produced hydrogen.

The scenarios are based on dynamic balances of energy demand and supply using detailed models to achieve consistency. The overall implications of each scenario are that fundamental changes of the whole energy system, economic structure and life-styles are necessary in order to achieve sustainable energy futures in Western Europe. The nature of the changes is different in each scenario.

ACKNOWLEDGMENTS

The study described in this report was made possible through the financial support of the Bundesministerium für Forschung und Technologie of the Federal Republic of Germany. The study team included the following researchers: Todor Balabanov, Richard Caputo, Karen Closek, Claire Doblin, Alois Hölzl, Wolfgang Korzen, Michael Messenger, Sabine Messner, Irving Mintzer, Nebojsa Nakicenovic, John Reuyl, Hans-Holger Rogner, and Toni Ward. Richard Caputo was the study coordinator from May 1979 to May 1981, and Wolf Häfele was the Project Leader.

The preparation of this report was greatly assisted by the support of William Keepin, Alan McDonald, Wolfgang Sassin, and Manfred Strubegger.

The report was translated into German by Ingrid Teply-Baubinder.

SOLAR ENERGY FUTURES IN A WESTERN EUROPEAN CONTEXT

Executive Summary

INTRODUCTION

The objective of this study, conducted under the sponsorship of the Bundesministerium für Forschung und Technologie (BMFT) of the FRG, is to investigate possible, though not necessarily probable, transition paths to a sustainable energy future for Western Europe. The analysis is based on three scenarios that dynamically balance energy demand and supply using detailed models to achieve consistency. Two scenarios consider exclusively solar futures--one is based on centralized solar technologies (Hard Solar scenario) and the other on decentralized, user-oriented technologies (Soft Solar scenario). The third scenario, based on nuclear technologies, incorporates an intermediate degree of centralization in the energy system and serves as a comparison to the two exclusively solar scenarios. 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, although it may be desirable. In any case it implies a transition away from domestic and imported fossil energy sources. While all three 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 all three scenarios require fossil energy imports during the transition period before the sustainable energy systems are fully implemented. The overall implications of each scenario are that fundamental changes of the whole energy system, economic structure and life-styles 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. For Western Europe, as a developed region with little endogenous fossil resources, this implies a transition to alternative energy sources such as nuclear, solar and renewable 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 time period, but enough time must pass to permit the fundamental infrastructural changes that are required in the scenarios.

THE SPATIAL SCOPE

In this study, Western Europe refers to continental Europe outside the COMECON countries and Asia Minor. It includes the 12 member countries of the European Community and in addition Austria, Finland, Norway, Sweden, Switzerland, Turkey and Yugoslavia. Clearly, Western Europe is not an entirely homogeneous entity, various countries have different resource bases (including a large variation of solar insolation between the North and the South), economic and political systems, industrial structures, and different levels of development. In order to account for some of these differences between the various parts of Western Europe, the countries were grouped into three more homogeneous areas which are labeled North, Central and South Europe, shown in Figure 1.

This grouping improves the homogeneity especially with respect to solar insolation and climate, but also to a lesser extent with respect to economic development and population growth.

BASIC ASSUMPTIONS

The future energy outlook for Western Europe depends on a multitude of interdependent factors--most important among these are the economic development and population growth. Therefore, the future evolution of Gross Domestic Product (GDP) and population are the two basic assumptions in the scenarios. The population evolution is based on projections developed by Keyfitz (1979) and shown in Figure 2 which indicates 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 percent in 1975 to 63 percent while the shares of North and Central Europe would decline from 6 to 4 percent and from 39 to 33 percent, respectively.

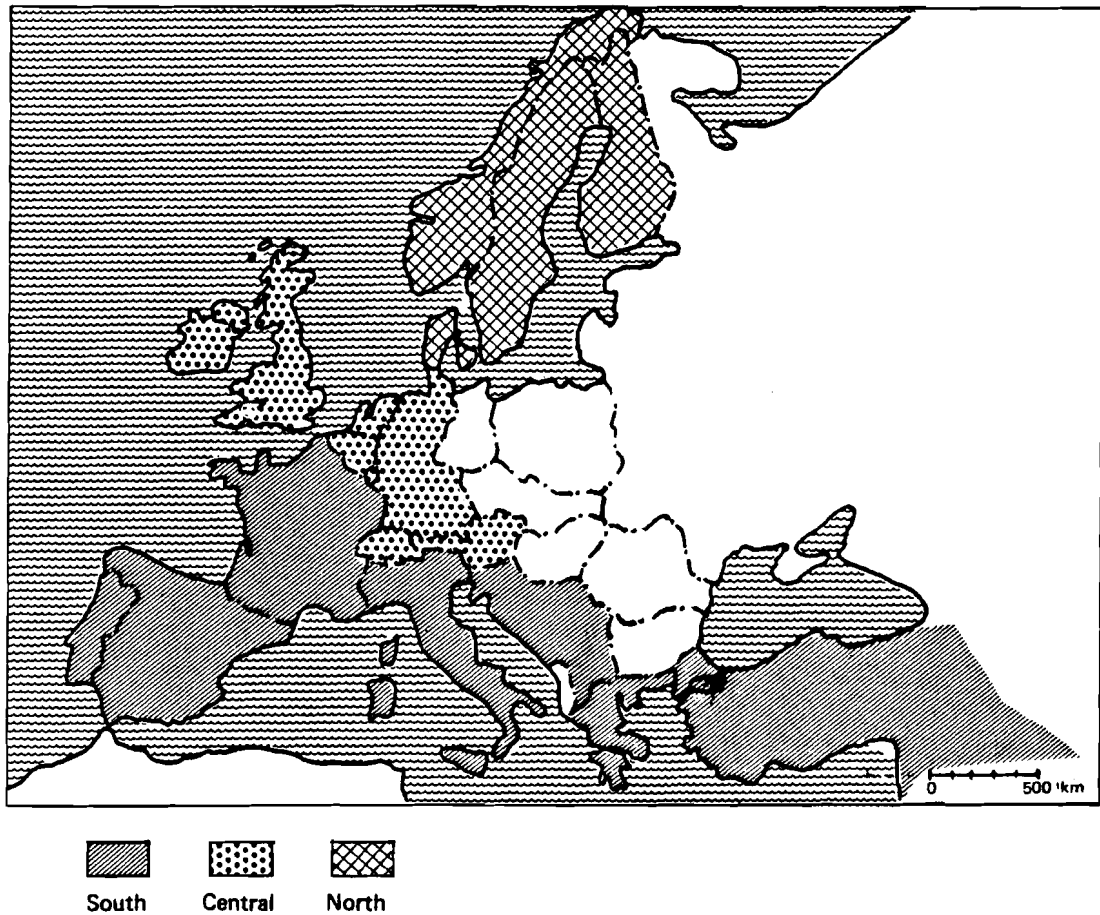


Figure 1. Western Europe.

The projection of the GDP evolution in the scenarios is based on the GDP growth in the Low scenario of the IIASA Global Study. Figure 3 shows the GDP evolution in Western Europe. The growth rates are the 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 percent per year growth rate, which may appear to be a low figure. However, this growth rate should be viewed as a sustainable long-term trend, and should be compared with a much lower population growth rate of 0.3 percent per year. On the average it leads to more than a five-fold increase in GDP per capita levels by the end of the next century.

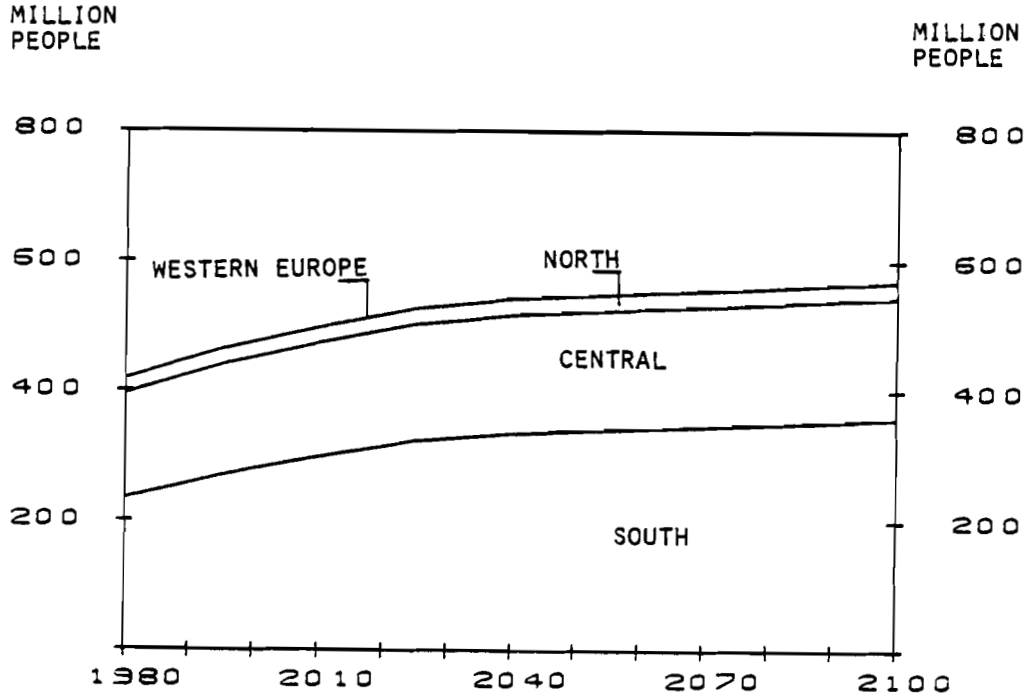


Figure 2. Population projection.

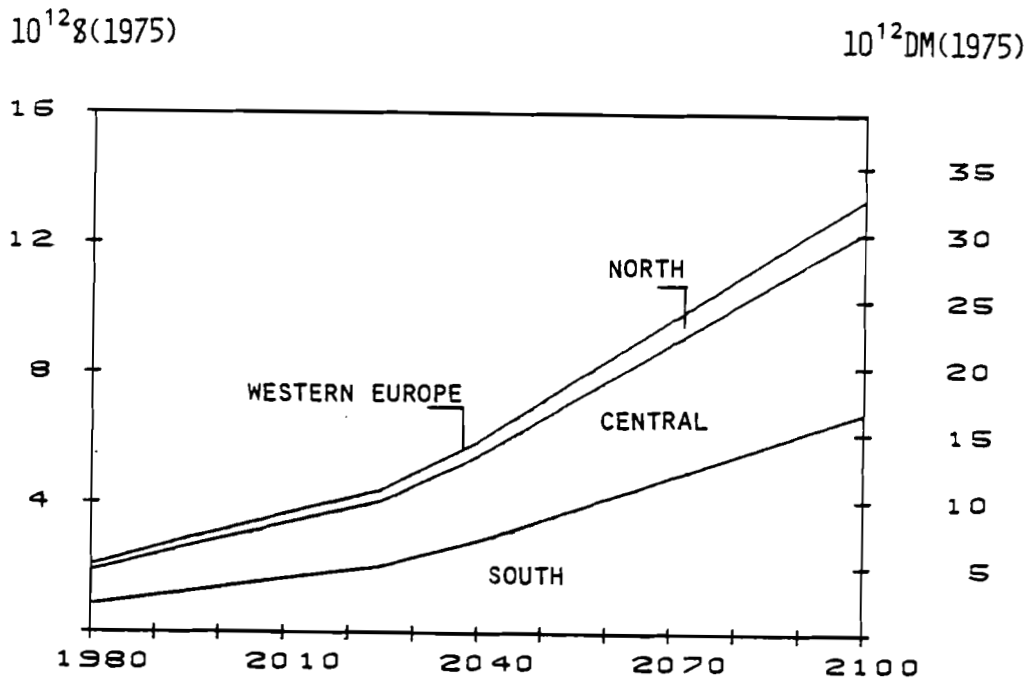


Figure 3. GDP projection.

THE ANALYTICAL APPROACH

The assessment of the energy outlook for Western Europe over a time period of more than 100 years is to some degree speculative since a completely comprehensive study of the future is impossible. This is the reason for the choice of a scenario approach that outlines the structures and patterns of our image of consistent futures. Perhaps the two most important qualitative assumptions behind the feasibility and consistency of the three sustainable scenarios are that we consider only a surprise-free future and assume a large degree of cooperation within Western Europe and in the world.

The scenarios should be viewed as a consistent framework for explicitly analyzing the consequences of the assumptions made. All quantitative assumptions, the consequent analysis, and the results, should be seen as means of describing qualitative features. Each scenario results in a quantitative energy balance throughout the energy system in meeting energy demands, however the significance of the precise numerical results is mainly important as a guarantee for consistency.

The three scenarios are formulated so as to provide three extreme alternatives for achieving a sustainable energy future in Western Europe. All three are based on practically infinite energy sources--solar insolation, nuclear energy in conjunction with breeding, and renewable energy forms. Two are based primarily on solar energy; 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 Nuclear scenario falls somewhere in the middle ground with a mixture of energy generation closer and further away from the user. The three 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 analyze 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. Being the extremes of conceivable energy futures, these scenarios are not very robust. Interdependencies are very severe, and they offer hardly any fall-back positions. In a sense they also do not allow for reversible decisions--each requires an all-out effort to be implemented. Thus a probable sustainable energy future for Western Europe would include a mixture from such extreme alternatives, and thus offer more resilience and more fall-back options if some of the crucial assumptions should not be fulfilled. Therefore, although these three extreme scenarios do not represent likely or even probable

futures, together they identify a *region of feasibility* within which more likely and more realistic sustainable energy futures for Western Europe could be found. Any future that is between these three extreme possibilities could be viewed as achievable. Thus, although the assessment of *the* future is impossible, the scenarios delimit the possibilities against the background of our assumptions.

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 life-style 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 life-styles 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 (i.e. economic activity) level are assessed in the MEDEE-2 model in physical terms and, in conjunction with energy use efficiency improvements and life-style 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 end uses results in useful energy, e.g. low temperature heat for space conditioning or gasoline for motor car propulsion. Ultimately, useful energy results in energy services, e.g. a well heated room or person-kilometers travelled by car.

The energy demand levels are assessed in the MEDEE-2 model for all sectors of the economy, e.g. 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, e.g. hydrocarbons for feed-stocks in chemical industry. The energy supply model MESSAGE II then determines the structure of an energy supply system that is capable of providing 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.

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

Final Energy Form	Final Energy Use		Coke	Feed-stocks	Motor Fuels	Elec-tricity	Total
	Thermal						
	Low	High					
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 1B. Final Energy by Form and Use, Hard Solar Scenario, 2100 (GWyr/yr)

Final Energy Form	Final Energy Use		Steel Production	Feed-stocks	Motor Fuels	Elec-tricity	Total
	Thermal						
	Low	High					
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 1C. Final Energy by Form and Use, Soft Solar Scenario, 2100 (GWyr/yr)

Final Energy Form	Final Energy Use		Steel Production	Feed-stocks	Motor Fuels	Elec-tricity	Co-generation	Total
	Thermal							
	Low	High						
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

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 (e.g. 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. 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 the GDP grows more than seven-fold 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 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 percent in the Soft Solar scenario (from 0.7 W/\$ (1975) in 1975 to 0.2 and 0.1 W/\$ (1975) 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 life-styles (e.g. 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 and Nuclear scenarios 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, represents the singular characteristic of a

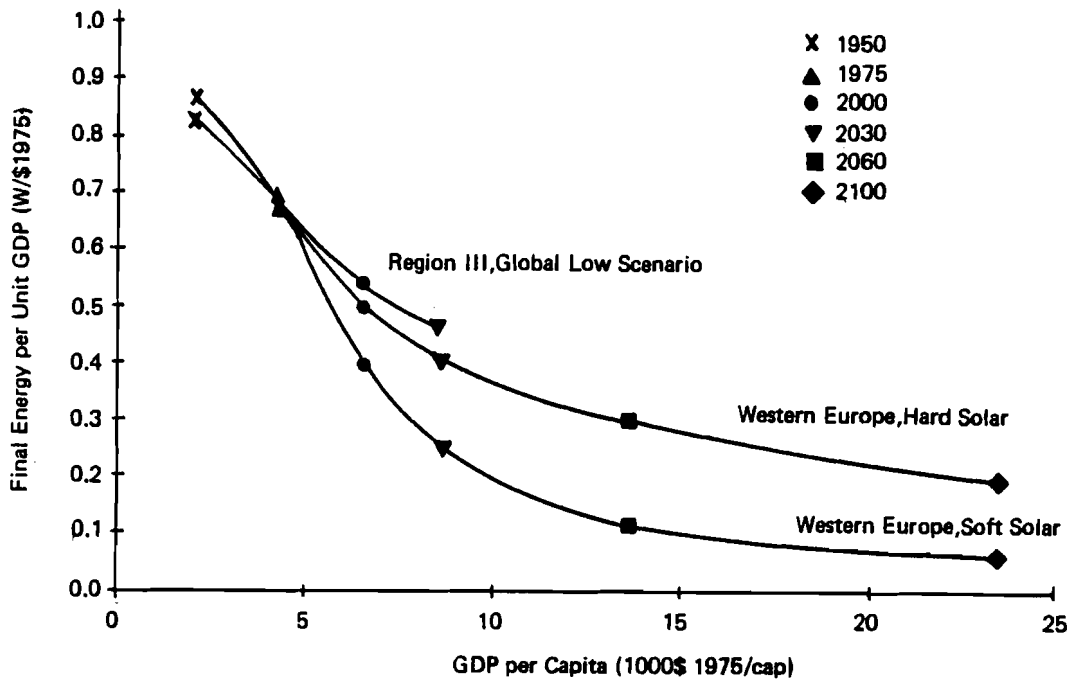


Figure 4. Energy intensiveness in the scenarios.

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 close as possible. The collocation of energy generation and conversion systems close 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 and Nuclear scenarios with their 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

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

Form	Base Year 1975	Scenario					
		Soft Solar		Hard Solar		Nuclear	
		2030	2100	2030	2100	2030	2100
Coal	10.1	4.6	0.1	14.5	0.1	10.6	0.1
Oil	59.5	6.6	0	15.2	0	12.1	0
Gas	16.4	4.2	0	21.8	0	11.0	0
Electricity	11.8	18.9	17.8	23.4	26.5	38.0	50.2
Biomass	2.2	9.8	7.9	5.3	3.1	5.7	3.1
Methanol	0	2.4	15.6	5.7	18.5	6.2	18.3
Hydrogen	0	13.5	14.9	14.1	51.8	15.4	28.3
District Heat	0	2.9	2.5	0	0	0	0
On-Site	0	37.1	41.2	0	0	0	0
Total (TWyr/yr)	1.19	1.17	1.39	1.82	2.81	1.69	2.82

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 percent of all final supplies. In addition, the local energy sources such as district heat co-generation and wind and photovoltaic plants contribute in the form of electricity 14 percent of final energy compared to the total of 18 percent of final energy delivered as electricity. The remaining electricity originates from hydropower. Only 15 percent of all final energy is delivered in the form of 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 percent of all final energy is delivered in the form of thermolytic hydrogen and 27 percent 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 percent 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-oriented, local or on-site systems.

With respect to final energy deliveries, the Nuclear scenario represents in many ways a mirror image of the Hard Solar scenario. The amounts of final energy delivered in the two scenarios are equivalent since they both balance the same levels and patterns of final and useful energy and energy service requirements. With respect to final energy forms delivered to end uses in the Hard Solar scenario the Nuclear scenario shows exactly the same biomass and methanol deliveries and in addition

parallel but exchanged roles of electricity and hydrogen. Although this result may appear surprising, it can be easily explained. Biomass is the only solid fuel left in all scenarios and as a source of carbon atom cannot be replaced by any other energy form. The same is true for methanol, all of it is needed to provide feedstocks in all three scenarios. Thus the amount of these two energy forms must be the same in the Nuclear and the Hard Solar scenarios, since they must satisfy the same energy demand levels. Hydrogen and electricity on the other hand are perfectly substitutable forms of energy in many energy demand categories. The main exception is the transportation sector. It needs a basically fixed proportion of hydrogen and electricity since by 2100 all free-range vehicles rely on hydrogen as an energy source and trains on electricity.

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 the Nuclear scenario such large storage capacities are not required. Nuclear power plants are better suited to operate in a base load mode (i.e. they do not have seasonal variations) thus to follow demand profiles some storage is also required but not to the extent as in the Hard Solar scenario. In other words, within the structure of the energy system and energy demand that have a common base in both scenarios, about one fourth of all final energy should be in the form of hydrogen, about one fourth in the form of electricity, and a little less than one fourth 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 percent 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) and in the Nuclear scenario as an opportunity to reduce the supply complexity by supplying the FBR generated electricity directly as electricity without further conversion. Table 2 shows that except for the electricity and hydrogen categories the final energy use patterns for the Nuclear scenario are essentially unchanged with respect to the Hard Solar scenario. Thus, in the two scenarios that are based on central energy conversion systems, hydrogen and electricity together provide almost 80 percent of all final energy. In the Soft Solar scenario the same relative share of final energy is provided by user-oriented systems, but although the hydrogen and electricity (relative) use is reduced, it is still needed. This stresses again the importance of these two energy carriers in the future. The symmetry is perfect: solar-thermal conversion needs the proton (i.e. hydrogen) more as an energy carrier because it can be easily stored, and nuclear energy needs the electron (i.e. electricity) more because it can be converted into an energy carrier at lower temperatures. But this freedom is limited, both energy sources must provide both energy carriers; the variation in the mix of these two energy carriers is limited to 50 percent. Thus the Nuclear scenario is similar to the Hard Solar scenario as far as the energy consumer is concerned--

both scenarios fulfill exactly the same energy demand categories.

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 and Nuclear scenarios 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 scenario is over 70 percent "soft", the Hard scenario relies more than 80 percent on centralized solar conversion and the Nuclear scenario is almost 90 percent nuclear. All scenarios rely exclusively on sustainable energy systems by the year 2100.

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

Energy Source	Base Year 1975	Scenario					
		Soft Solar		Hard Solar		Nuclear	
		2030	2100	2030	2100	2030	2100
Coal	22.1	2.4	0	12.6	0	5.1	0
Oil	52.5	3.6	0	9.5	0	6.1	0
Gas	13.2	2.3	0	13.7	0	6.0	0
LWR	2.4	4.6	0	0.8	0	5.8	0
FBR	0	0	0	9.5	0	56.2	65.3
HTR	0	0	0	0	0	5.5	23.9
(Nuclear Total)	(2.4)	(4.6)	(0)	(10.3)	(0)	(84.0)	(89.2)
Hydropower	8.1	10.6	8.5	7.7	4.3	6.6	3.4
Biomass	1.7	8.4	15.1	10.1	9.4	8.7	7.4
Windpower	0	34.8	33.9	0	0	0	0
Wavepower	0	1.8	1.4	0	0	0	0
Photovoltaics	0	6.0	9.4	0	0	0	0
On-Site Sources	0	25.4	28.3	0	0	0	0
("Soft" Total)	(0)	(68.0)	(73.0)	(0)	(0)	(0)	(0)
Solar-Electric	0	0	0	19.9	3.4	0	0
Solar-Hydrogen	0	0.1	3.4	16.2	82.9	0	0
("Hard" Total)	(0)	(0.1)	(3.4)	(36.1)	(86.3)	(0)	(0)
Total (TWyr/yr)	1.53	2.36	3.16	3.20	5.76	3.70	7.32

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 Nuclear scenario it consists of the converter and breeder reactor systems and in the Soft Solar scenario, of the local solar energy sources, such as the roof-top collector or the small neighborhood 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 minimization, a cost penalty is levied on technologies which do not belong to the "reference system". The following cost penalty structure is used--2.4 percent per year cost increase of fossil resources, natural uranium and nuclear system investment costs (except in the Nuclear scenario where nuclear technologies are the "reference system"). In addition, in the Soft Solar scenario cost subsidies of 40 percent for local and 60 percent 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 suited under the given constraints.

Thus, the general approach is that all energy conversion, transportation and distribution technologies can compete to meet demands in all 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 the import dependence is reduced in all scenarios by 2030. In 1975, 53 percent of all primary energy consumed in Western Europe originated abroad. By 2030, only two percent of all primary energy is imported in the Soft Solar scenario. A relative reduction of energy imports to 31 percent of all primary energy is also achieved in the Hard Solar scenario, while the Nuclear scenario achieves reductions of energy imports comparable to the Soft Solar scenario, at a little more than six percent. 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 sce-

nario due to increased hydrogen needs. In the other two scenarios 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, although 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 that 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. For precisely the same reason the Nuclear scenario also corresponds to the Higher demand projection. The difference between the two, however, is that the Hard Solar scenario needs additional hydrogen imports whereas the Nuclear scenario results in import independence. 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 both from the perspective of the user and energy supply infrastructure. It is possible to observe some analogies 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 sustainable 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: fuel wood, 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 life-style 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 import of fossil energy.

By the year 2100 in the Soft Solar and Nuclear scenarios it would be possible for Western Europe to become self-sufficient 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 capital requirements to implement the Hard Solar scenario. Thus, in the Hard Solar scenario, Western Europe has both the burden to invest in the development of hydrogen production outside its borders, and to pay 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 the higher solar insolation and cheaper labor, 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 (e.g. 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 U.S. dollars at 1975 prices and exchange rates. They express cost-prices 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 time periods. However, such a model does not exist. Therefore we cannot analyze, 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 a position to evaluate the reasonableness of our GDP growth assumptions with respect to ability of the Western European economy to pay for the specified energy imports.

We can, however, compare the relative share of payments for energy imports in total GDP given in Figure 5. In the Hard Solar scenario the total energy import bill increases from less than 5 percent in 1980 to a maximum of almost 7 percent 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 percent of the import bill is due to fossil energy imports and the remainder due to hydrogen imports from the Sahara.

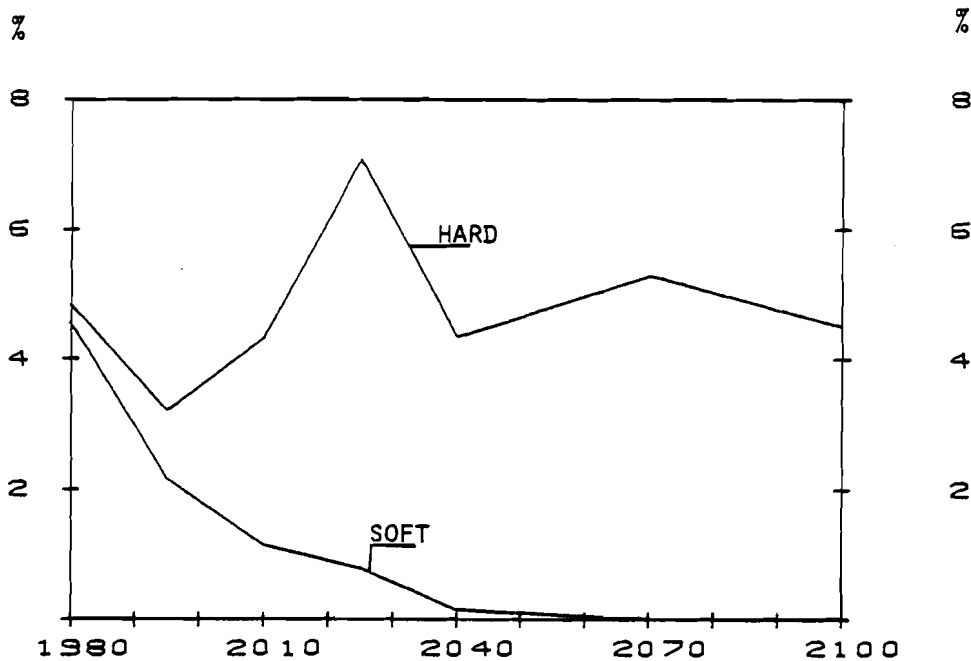


Figure 5. Cost of energy imports as share of GDP, Hard and Soft Solar scenarios.

In the Soft Solar and Nuclear scenarios the energy import bill is very low. Already by 2030 less than one percent of total GDP goes for energy imports, and by 2100 no energy is imported. This gradual decrease of the relative share of the energy imports and eventual import independence in the Soft Solar and Nuclear scenarios 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 percent 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 (e.g., in the FRG the share of energy imports in GDP was 3.1 percent 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 payments deficits, in the long-term future, although 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 towards environmental impacts of the energy system and all economic activities. Thus energy and other conservation measures along with 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 6 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 percent in 2030 and gradually doubles by 2100. In the Soft Solar scenario it increases somewhat up to 2030 and slowly reduces to below 3 percent of GDP by 2100. Thus, due to the continuous economic growth, the energy investment share in GDP even in the Hard Solar scenario appears not to be too critical, although in absolute terms the energy investment requirements increase by a factor 13 in the Hard Solar scenario and by a factor 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 U.S. 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 end use 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-oriented 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 the 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

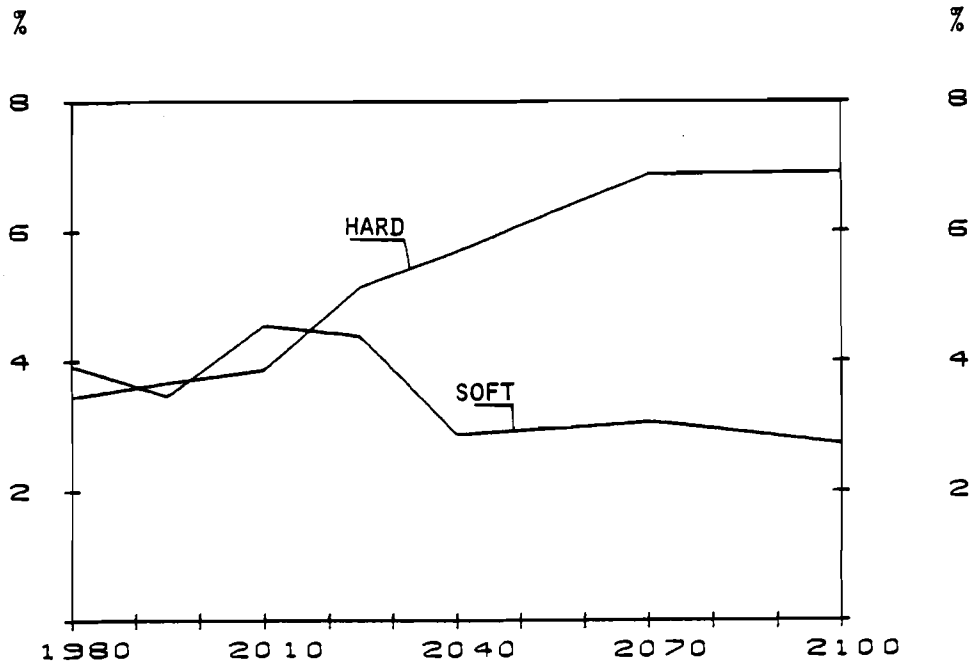


Figure 6. Capital requirements as share of GDP, Hard and Soft Solar scenarios.

for almost one 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 employment of foreign unskilled labor. 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.

The higher capital requirements for end use and on-site technologies illustrate that both energy conservation and user orientation could relieve many of the traditional energy supplies from centralized energy systems. Thus higher investments can help to reduce the increase of the total energy bill by reducing energy demand and increasing the amount of energy generated locally. However, there is an additional factor implied by the scenarios that is not explicitly reflected in the capital needs: namely, the indirect capital needs that would result from lifestyle changes and infrastructural changes.

However, these structural changes are so numerous in the scenarios that they cannot all be accounted for in monetary terms. This is exactly the reason why the energy demand model MEDEE-2 was used to account different energy needs in physical terms for the projected GDP levels. In other words, we have assumed that continuous economic growth would lead to a substitution of capital for energy throughout the economy and not only in the energy sector itself. Although reduced economic growth would also lead to reduced energy needs and structural changes in the economy, the reduction would be of a different nature. It would imply a change in life-styles based on curtailments rather than on substitution between factors. In summary, direct investment needs of the energy sector would definitely increase over the next 100 years in Western Europe, and their relative share in GDP would also increase during the next 50 years. Given the quite favorable economic environment of the scenarios, these increases would cause increases in real capital costs, but should not lead to insurmountable problems. However, given the state of the art of long-term economic modeling, this can be viewed as an assessment and not as a definitive answer, since there is no guarantee that the assumed economic growth is realizable. This depends on a host of other factors not considered in the analysis.

This result indicates that the centralized and decentralized scenarios basically cannot be compared with respect to required investments or energy costs since each of them implies an essentially different economic structure in the future that is different from the current one.

But the analysis of the energy systems in the scenarios has demonstrated that a consistent energy supply and demand balance can be achieved in a sustainable energy future of Western Europe if appropriate changes in life-styles and economic structure are consistent and possible.

CONCLUSION

The study shows that after a period of some 100 years virtually all energy demand categories could be supplied on a sustainable basis from solar and renewable energy sources. Thus it would be tempting to conclude that such a future is within our reach. But the analytical approach could only designate technical and techno-economic solutions that indicate how such a transition could be achieved. Behind these solutions, however, are the two sets of normative assumptions that specify a parallel, and within scenarios necessary, evolution of life-style patterns and economic structure. In the previous section we have attempted to show why these aspects of the scenarios cannot be treated together with other scenario implications with the same analytical approach that was based on physical balances and monetary flows in real terms. In other words, it was possible to determine what types of structural changes are necessary in order to achieve a balance within the energy system, but it is not possible to assess the quantitative feedbacks throughout the society in the same manner as within the energy system. It is simply not possible to com-

pare different economic structures and consumer habits with current measures. For these reasons the scenarios should not be viewed as predictions of a likely future for Western Europe. The scenarios cannot be viewed as immediate alternative options for Western Europe as it exists today either, since each scenario necessitates complete but different changes of the current socioeconomic structures. Rather, they represent "yardsticks" that delimit the range of feasible and consistent futures given the assumptions. A choice between the scenarios would certainly not depend on preferences for certain technologies but on social, cultural as well as political preferences. These changes of preferences would affect Western Europe as it exists today more dramatically than the associated technological changes of the energy system, although in the scenarios both are necessary.

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