Working Paper

SOLAR ENERGY FUTURES IN A WESTERN EUROPEAN CONTEXT

Final Report

N. Nakicenovic
S. Messner

December 1982
WP-82-126/b

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 but different 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

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SOLAR ENERGY FUTURES IN A WESTERN EUROPEAN CONTEXT

1. INTRODUCTION

Problem Definition and Objectives

The objective of the study is to investigate the possibility of a transition to sustainable energy systems based on solar energy in Western Europe. By sustainable energy systems wo do not mean necessarily that import dependence is completely alleviated, but that continued energy supply is assured from practically infinite energy sources. This then implies a transition away from domestic and imported fossil energy sources.

This study was conducted under the sponsorship of the Bundesministerium für Forschung und Technologie (BMFT) of the FRG, 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. For this to be possible a reasonable degree of economic growth is necessary above the population growth. To assure such a degree of continued growth one of the prerequisites is energy availability. As the available fossil energy sources become increasingly dirtier, harder to exploit and therefore more expensive, it is crucial that at least the developed parts of the world should phase out the fossil energy sources, needed in the developing countries, as soon as possible. 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 sources.

The sustainable energy sources considered in the study include solar insolation converted to useful forms of energy by various technologies ranging from a relatively simple roof-top collector to a large central receiver solar power plant. We also considered other alternative energy sources which can provide energy on a practically unlimited continual basis. They include nuclear energy in conjunction with fast breeder reactors. The breeder reactors can decouple nuclear energy from natural uranium requirements so that its potential also becomes practically unlimited. Finally, we considered a wide range of renewable energy sources from biomass to hydropower.

From these primary energy forms available on a sustainable basis, energy is transformed and transported until it is available at consumption nodes in useful forms for the final consumer. This infrastructure for sustainable energy systems is in general different from the current one. The present day energy system in Western Europe is based on fossil fuels and some hydropower and nuclear energy. Oil takes the largest portion in meeting the energy requirements. It is transported easily over large (intercontinental) distances of more than 1000 km, it is stored easily and requires relatively little conversion (refining) until it can be distributed to the user. Most of these convenient characteristics of oil are due to its liquid form and relatively high energy density of about 10 000 kcal/kg. Natural gas requires almost no conversion (unless it is used to generate electricity), but it is harder to transport, it requires a pipeline network both for transport and distribution. Coal, on the other hand, is harder to extract from the ground and harder to transport and distribute to final users. Electricity is the most convenient form of energy, it is clean and easy to use, but it also requires a network for distribution and power plants for conversion of primary energy forms such as coal, oil and natural gas. Thus, electricity is a convenient energy carrier for distribution of energy after it has been converted from its primary form, especially in the case of coal which is hard to transport to the user without this conversion step.

Energy System Configuration

In the study we consider two types of sustainable energy systems. The first category includes systems that in general are expected not just to rely on larger distribution networks, but also to involve extensive conversion of primary energy forms into forms that are directly useful to the consumer. Electricity and hydrogen are two of the most important final energy forms since they are both relatively easy to transport to the consumer (although hydrogen is easier to transport than electricity over large distances of, say, more than 1000 km). A third energy form comprises the synthetic liquid fuels which have similar properties to oil and its refinery products. In the study, synthetic liquid fuels are generated using hydrogen and the carbon atom from biomass. Thus, in principle, two energy forms are generated from the sustainable energy sources, the electronic (electricity) and the protonic (hydrogen) forms. They are then either directly consumed or used to generate useful energy. This is a general characteristic of all envisioned sustainable energy systems that involve remote energy generation and large-scale energy transportation and distribution to consumption nodes. Such energy systems we call "hard" systems since they involve large-scale generation of energy and complex transportation, conversion and distribution infrastructure.

On the other side of this scale are the sustainable energy systems that generate low to medium temperature heat or electricity close to consumption nodes (or on-site) and involve very little or no transportation and distribution infrastructure. Such energy systems we call "soft" systems.

The Analytical Approach

The solar energy future for Western Europe is characterized in this study by two extreme scenarios: the Hard Solar scenario that relies mostly on solar systems with large-scale energy transportation from southern to northern parts of Europe and large distribution systems, and the Soft Solar scenario that relies mostly on local solar systems.

The Hard Solar scenario relies primarily on large-scale solar thermal power plants for energy generation. They are located throughout South Europe, from Portugal to Turkey. Both electricity and hydrogen are generated, electricity is transported to other parts of Europe via DC power lines, and hydrogen is produced either by thermolysis or by electrolysis on site and is then transported via pipelines to consumption centers. Two modes of energy storage are used to balance the discrepancies between the solar insolation and demand loads. For electricity, mainly pumped underground hydro storage is used, and for hydrogen the long-distance pipeline itself has the capacity for daily storage. To balance seasonal variations, underground hydrogen storage is used.

In the Soft Solar scenario, the highest priority is allocated to the implementation of on-site solar systems such as the rooftop collector, active and passive solar heating, and local cogeneration plants. Only as the potentials of such systems are exhausted are more remote systems used to supplement the local energy supply, starting from district systems and going to the national level. Only when these possibilities have been exhausted are continental energy supply systems considered.

In both Hard and Soft Solar scenarios biomass is used to produce liquid fuels for such uses where hydrogen and electricity cannot easily substitute liquids, e.g. feedstocks. Thus, the two Solar scenarios can be located at the opposite sides of the decentralized and centralized energy generation and distribution systems. The Hard scenario relies mostly on remote generation in South Europe and long-distance energy transport and the Soft scenario on on-site and local generation with very little energy transport needs.

As a basis for comparison, and in contrast to these two Solar scenarios, a Nuclear scenario that relies on nuclear energy as much as possible is also investigated. Only one nuclear scenario is considered, but it includes a mixture of different nuclear systems. The conventional reactors with relatively simple fuel cycles (i.e. those that require mainly the front end of the fuel cycle) are represented as well as more advanced breeder and high converter designs. The reactors that are connected with the electricity grid require little energy transport and are relatively close to the consumption centers. The more advanced reactors with complete (closed) fuel cycles could also be placed in energy centers that are more remote from consumption nodes and involve large-scale energy transportation and distribution. However, energy transportation requirements would be limited to 1000 km or less, whereas in the Hard Solar scenario electricity and hydrogen produced in sunny areas are transported over distances of more than 1000 km to consumption centers. The solar energy transportation and distribution system is also more complex since daily and seasonal storage of energy is required in order to balance the discrepancies between solar insolation and energy demand profiles.

In this sense, the three scenarios define 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 little average transport needs and the Hard 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 consumption nodes. The three scenarios outline the limits of what is feasible from the point of view of the configuration of the whole energy system. Feasibility constraints such as these are usually more stringent than mere resource limits, 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. These three extreme scenarios thus do not represent a most likely or even probable future. They are constructs designed to analyze the limiting factors when one particular sustainable energy option is utilized to the largest extent possible. Together they *define* *a region* within which more likely and more realistic sustainable energy futures for Western Europe could be found. They *test the extremes* of physically possible, yet 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--they all require an all-out effort to be implemented. Thus a probable sustainable energy future for Western Europe would include a mixture of such extreme alternatives, and thus offer more resilience and more fall-back options if some of the crucial assumptions should not be fulfilled.

Therefore, the report does not offer an optimal sustainable energy strategy for Western Europe, it also does not deal with the question of which future developments are more likely to be actually implemented. Instead, it is a prescriptive analysis of limiting cases that delimit the actual deployment of energy technologies. It outlines the area of flexibility (feasibility) for research and development efforts in Western Europe that would lead to a sustainable energy future. Thus the future energy system should be limited to the discussed flexibility region, otherwise substantial discrepancies between the overall economic growth and energy sector might be unavoidable. Our scenarios show that in those limiting cases the investment requirements of a consistent, but extreme energy system tend to cause departures from the overall economic equilibrium.

2. THE IIASA GLOBAL ENERGY STUDY

The Global Energy System

In order to place the scope and the objectives of the Solar Energy Study for Western Europe in perspective, it is necessary first to identify the global aspects of the current energy situation and the future prospects.

In 1975 more than 40 percent of globally consumed oil came from the Gulf states. The abrupt rise in the price of oil in 1973/74, made possible by a set of political, economic and social conditions which evolved in the world, placed most of the world's economies under severe stress. The higher price of oil has made it increasingly difficult for most of the industrialized countries to sustain and continue the high rate of economic growth and energy consumption initiated in the 1950s and 1960s. In addition, as the developing regions of the world undergo a process of industrialization, they will require increasing amounts of energy while the industrialized regions will need more energy to sustain their economic growth and avoid stagnation. Since 1950 the increase in commercial energy consumption has been three-fold in the industrialized countries and about eight-fold in the developing regions. However, the relative energy consumption gap has not been narrowed down: With 70 percent of the world's population the developing countries share only 14 percent of the primary energy consumed world-wide. All this points to the truly *global* interdependence of the world's energy system.

Thus, while it is recognized that sufficient availability of energy is necessary for continued economic growth and improvement of human welfare, the impacts of human activities on the environment in general, and those associated with energy use in particular, are no longer considered small and negligible. The energy availability is increasingly more constrained through higher prices, resource depletion and environmental constraints. The resources are *finite*, or more exactly, they are becoming more expensive and harder to exploit, due in part to environmental constraints.

In detailed national analyses of energy demand and endogenous supply, the balance is generally expected to come from imports. If the world's energy resources were infinite, this expectation would be reasonable. But given that resources are not infinite, the question then arises whether someone else has counted on the same barrel of oil or ton of coal. A global view is necessary to account and balance all import needs against export availabilities.

Two Global Scenarios

The Energy Systems Program of the International Institute for Applied Systems Analysis (IIASA) conducted a seven-year study, which involved 140 scientists from 20 countries, in order to encompass some of these complex factors affecting the present energy problem and in order to provide a better understanding of the long-term, global energy prospects and options. The results of this study are described in the recently published reports "Energy in a Finite World" (Energy Systems Program Group, 1981). Within the global Study two scenarios are identified for the seven world regions (see Figure 2.3) which indicate a possible transition from the current energy demand and supply based on relatively cheap, clean and easily accessible fossil energy sources towards a more advanced if not sustainable energy system.

The quantitative and detailed analysis of energy demand and supply in the two scenarios spans the time period of 50 years reaching out to the year 2030, although other parts of the Global Study looked even further into the future. Such a long time horizon is necessary in order to encompass fundamental changes in the energy system. Figure 2.1 shows that in the past it took 50 years before oil and natural gas replaced about one-third of the traditional uses of coal. The fundamental changes have required even longer periods; it took 100 years before fuel wood, the major source of energy before the 1850s, was replaced by fossil fuels. Today the energy system is characterized by long lead times so that it may take 100 years or more before fundamental changes of the energy supply pattern could lead to a situation where oil and gas may no longer be the dominant energy sources. Thus, 50 years, or two power plant generations, is the time span necessary to analyze major technological changes of the energy system. In addition, it is anticipated that the next

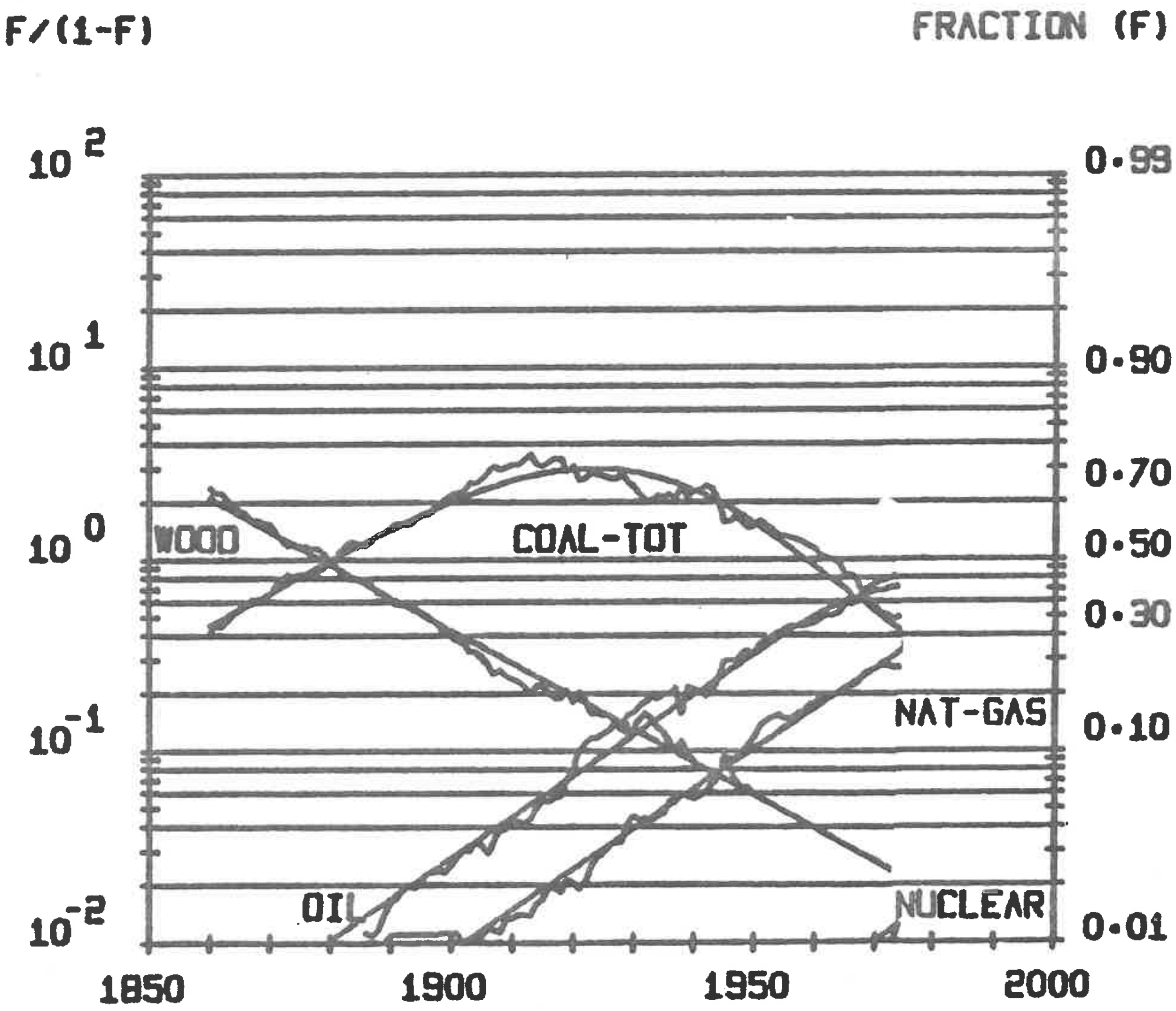


Figure 2.1. Global primary energy substitution. Logarithmic plot of the transformation f(1-f) where f is the fractional market share. Smooth lines are model estimates of historical data; scattered lines are historical data; straight lines show the logistic model substitution paths.

50 years coincide with what is anticipated to be the steepest ever increase in global population. A time span of 50 years also encompasses two human generations, which may be necessary before a stable world population is reached. The population growth in the two scenarios is based on the projections of Keyfitz (1979) which envisage a doubling of the world population from 4 billion in 1975 to 8 billion by the year 2030 as shown in Figure 2.2. Thereafter it is expected that the world population would achieve an asymptotic level.

The aim of the two scenarios was to cover the entire globe, yet it was impractical and probably impossible to include all of the 140 or so national cases separately. Thus, in order to encompass the important national differences, the globe was divided into seven regions, partially based on geographic proximity, but more so on similarity of the main economic and energy characteristics. Figure 2.3. shows the seven world regions. Region I, North America, has developed market economies and is rich in resources. Region II, the Soviet Union and Eastern Europe, has developed planned economies and is also rich in resources. Region III, member countries of the Organisation for Economic Cooperation and Development (OECD, except North America), has developed market economies and is poor in resources. Region IV is Latin America. Region V, Southeast Asia and Africa, has developing economies with high population and is relatively poor in resources. Region VI consists of the relatively oil-rich Gulf countries; and Region VII of the planned Asian economies.

Each of the two quantitative global scenarios, based on the assumption of global cooperation, balances the energy demand and supply for the seven world regions over the time horizon of 50 years. They are labeled High and Low, the former referring to a global situation by 2030 in which world energy demand is relatively high but still manageable with a value around 36 TWyr/yr (implying a 4.3-fold increase over the 8.2 TWyr/yr in 1975), the latter referring to a situation in which the demand is relatively low with a value around 22 TWyr/yr (a 2.7-fold increase of the 1975 value). These scenarios are benchmark figures and not predictions of future energy demand. Only one future is possible but two alternative energy demand scenarios were intentionally

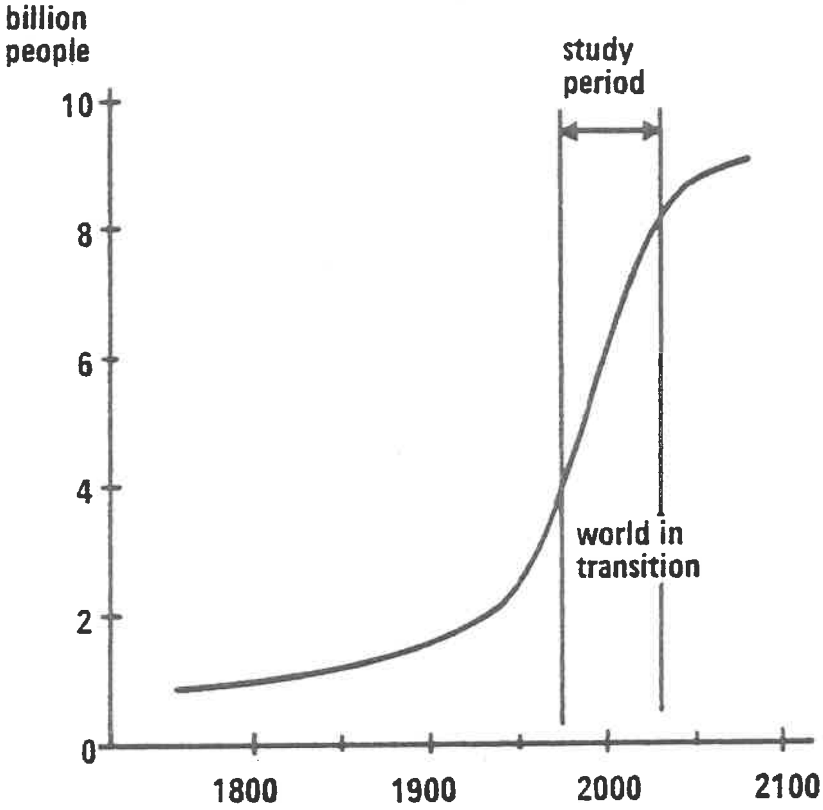
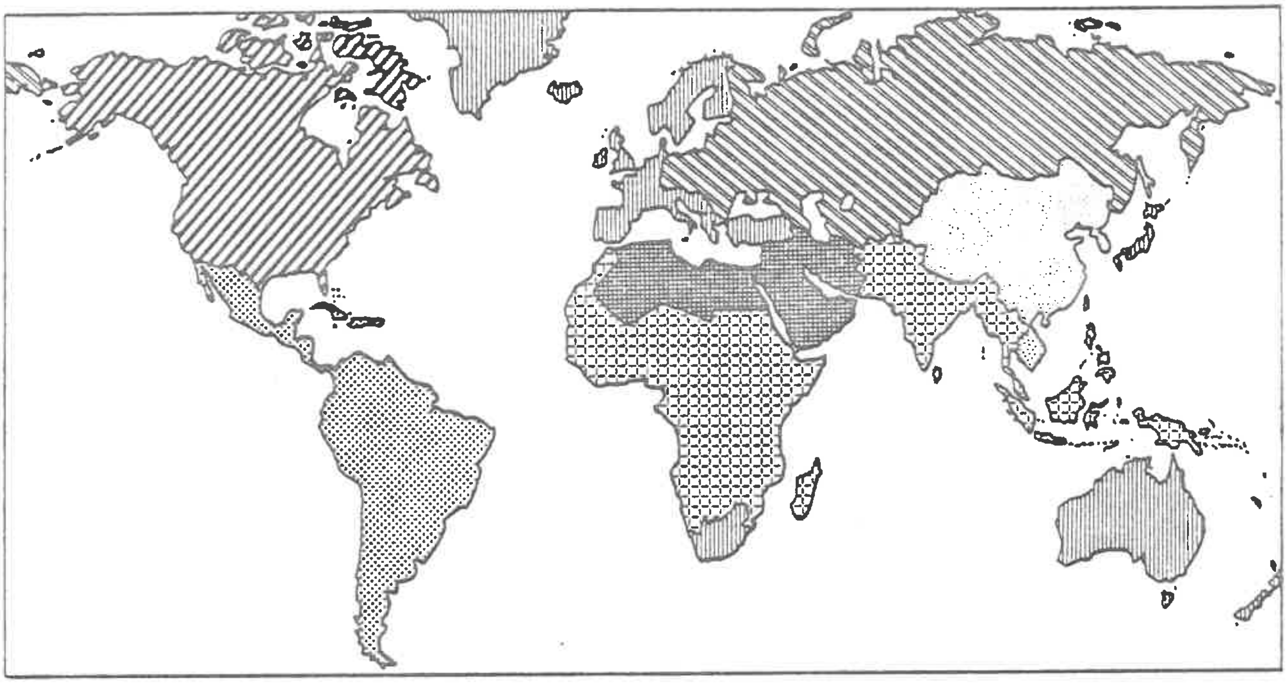


Figure 2.2. World population, historical and projected.
SOURCE: Keyfitz (1979).



▨	REGION I	(NA) NORTH AMERICA
▧	REGION II	(SU/EE) THE SOVIET UNION AND E. EUROPE
▥	REGION III	(WE/JANZ) W. EUROPE, JAPAN, AUSTRALIA, NEW ZEALAND, S. AFRICA, AND ISRAEL
▒	REGION IV	(LA) LATIN AMERICA
▦	REGION V	(Af/SEA) AFRICA (EXCEPT NORTHERN AFRICA AND S. AFRICA), SOUTH AND SOUTHEAST ASIA
▩	REGION VI	(ME/NAf) MIDDLE EAST AND NORTHERN AFRICA
□	REGION VII	(C/CPA) CHINA AND CENTRALLY PLANNED ASIAN ECONOMIES

Figure 2.3. The IIASA world regions.

considered. They concentrate on physical, engineering and economic aspects of the energy transition. They do not explicitly take into account the institutional, political and most social aspects of the possible energy futures, although they are meant to provide a framework within which to deal with these issues.

Economic Growth and Energy Demand

Besides the population growth and resource availability, the future economic development is one of the principal factors affecting the energy demand and supply opportunities. The economic growth in the scenarios is lower than during the past decades in all regions of the world. Indeed, the conditions for interregional consistency, the balance of trade and energy supply and demand in the scenarios generally limited the economic growth opportunities. Consequently, the GDP (Gross Domestic Product) growth assumptions are conservative, resulting in an average 3.3 percent per year increase of GDP between 1975 and 2030 in the High scenario and 2.3 percent per year in the Low scenario. Both scenarios anticipate declining GDP growth rates over the next 50 years.

Table 2.1 gives the disaggregated GDP growth rates by region for both scenarios. As can be seen from the table, the economic growth rates even in the High scenario are considerably lower than the historically observed ones, although the per capita growth rates of the developing regions (IV, V, VI, VII) exceed those of the developed ones (I, II, III). However, the economic development "gap" is not substantially narrowed, especially in the Low scenario. We stress that the growth rates do not reflect the desires and aspirations for development in each region. The Low scenario, in particular, may be unacceptably low in many regions. Even the growth rates of the High scenario fall short of the aspirations of a New Economic Order.

The population and economic growth are the principal determinants of energy demand in the scenarios. 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

Table 2.1. Historical and Projected Growth Rates of GDP by Region, High and Low Scenarios, 1950-2030 (%/yr)

A. High Scenario

	Historical		Scenario Projection			
Region	1950-1960	1960-1975	1975-1985	1985-2000	2000-2015	2015-2030
I (NA)	3.3	3.4	4.3	3.3	2.4	2.0
II (SU/EE)	10.4	6.5	5.0	4.0	3.5	3.5
III (WE/JANZ)	5.0	5.2	4.3	3.4	2.5	2.0
IV (LA)	5.0	6.1	6.2	4.9	3.7	3.3
V (Af/SEA)	3.9	5.5	5.8	4.8	3.8	3.4
VI (ME/NAf)	7.0	9.8	7.2	5.9	4.2	3.8
VII (C/CPA)	8.0	6.1	5.0	4.0	3.5	3.0
World	5.0	5.0	4.7	3.8	3.0	2.7
I + III[a]	4.2	4.4	4.3	3.4	2.5	2.0
IV + V + VI[a]	4.7	6.5	6.3	5.1	3.9	3.5

B. Low Scenario

	Historical		Scenario Projection			
Region	1950-1960	1960-1975	1975-1985	1985-2000	2000-2015	2015-2030
I (NA)	3.3	3.4	3.1	2.0	1.1	1.0
II (SU/EE)	10.4	6.5	4.5	3.5	2.5	2.0
III (WE/JANZ)	5.0	5.2	3.2	2.1	1.5	1.2
IV (LA)	5.0	6.1	4.7	3.6	3.0	3.0
V (Af/SEA)	3.9	5.5	4.8	3.6	2.8	2.4
VI (ME/NAf)	7.0	9.8	5.6	4.6	2.7	2.1
VII (C/CPA)	8.0	6.1	3.3	3.0	2.5	2.0
World	5.0	5.0	3.6	2.7	1.9	1.7
I + III[a]	4.2	4.4	3.1	2.1	1.3	1.1
IV + V + VI[a]	4.7	6.5	5.0	3.8	2.9	2.6

[a] Presented for purposes of comparison with data of WAES (1977) and of other global studies which exclude centrally-planned economies.

NOTE: Historical and projected values of GDP in constant (1975) U.S. dollars are given in Chant (1981).

gasoline or electricity.

The aggregate final energy demand in the seven world regions accounts for substantial energy savings and reflects the assumed conservation measures in the scenarios. The energy savings result not only from structural changes throughout the economy and demand reductions, but also from improved energy use efficiencies that lead to higher energy "productivity". However, all of these improvements in energy use are constrained by higher costs and by time: To retrofit the old houses for better insulation or to replace a housing stock by more energy efficient buildings takes anywhere from a few years to a few decades, to retool the existing production or to build new factories based on more efficient technologies can take from one decade to up to the plant lifetime. These constraints are reflected in the energy demand accounts of the two scenarios. Table 2.2 shows the resulting final energy demand in the two scenarios by region. As a comparison, the final energy demand levels are given that were calculated using historical (1950 to 1975) final energy-to-GDP elasticities for each region. Thus, substantial final energy demand reductions of up to 50 percent are realized in all regions when compared with historical trends. On the average the reductions are higher in the High scenario mainly due to the higher level of economic growth in this scenario.

Figure 2.4 shows the final energy per GDP plotted against GDP per capita evolution in the scenarios. It illustrates the extent of energy efficiency improvements and savings throughout the whole economy. In the past the decrease of energy intensiveness (final energy per GDP) during the period of economic growth (increases in GDP per capita) was realized only in Regions I and II. In the scenarios a decline in energy intensiveness can be also observed in Region III. This trend characterizes a phase of post-industrial development, while the developing regions (IV, V and VI) undergo a phase of industrialization in the scenarios accompanied by increases in energy intensiveness. In other words, the developed regions need relatively less energy in the scenarios to sustain further economic growth and the developing parts of the world more. The average global reduction of energy intensiveness is from 0.91 Wyr/yr per dollar (1975)

Table 2.2. Final Energy in the Two Scenarios Compared to Final Energy Calculated with Historical Elasticities, 2030

Region	High Scenario (GWyr/yr)	With Historical ε_f[a] (GWyr/yr)	Difference[b] (%)	Low Scenario (GWyr/yr)	With Historical ε_f[a] (GWyr/yr)	Difference[b] (%)
I (NA)	3,665	6,921	47	2,636	4,036	35
II (SU/EE)	4,114	5,355	23	2,952	3,850	23
III (WE/JANZ)	4,375	6,037	28	2,987	3,761	21
IV (LA)	2,641	4,385	40	1,656	2,481	33
V (Af/SEA)	3,175	6,900	54	1,876	3,121	40
VI (ME/NAf)	1,620	2,590	37	850	1,015	16
VII (C/CPA)	3,196	8,849	64	1,589	3,536	55
World	22,786	41,037	44	14,546	21,800	33

[a] Calculated using historical (1950-1975) final energy-to-GDP elasticity for each region (ε_f).

[b] Calculated as final energy using historical elasticities minus IIASA scenario projection divided by final energy using historical elasticities.

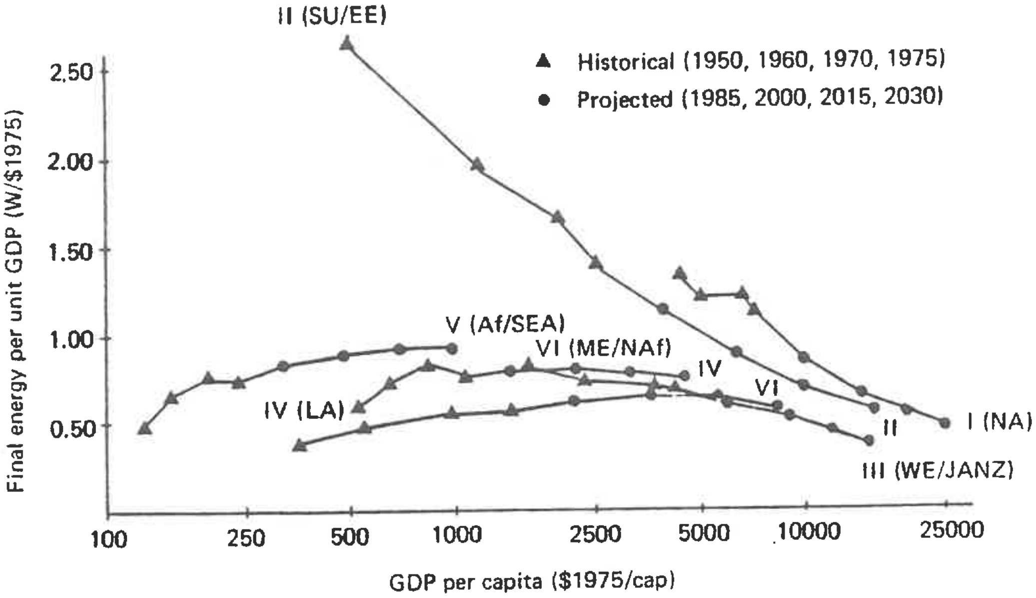


Figure 2.4a. Energy intensiveness in different world regions, High scenario.

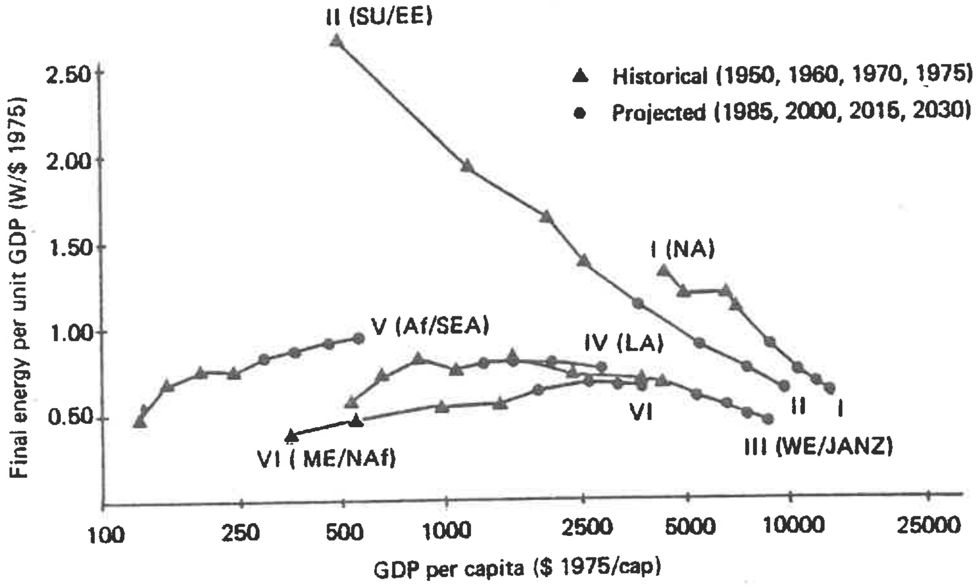


Figure 2.4b. Energy intensiveness in different world regions, Low scenario.

of realized GDP in 1975 to 0.53 Wyr/yr per dollar (1975) in the High scenario, and 0.62 Wyr/yr per dollar (1975) in the Low scenario by the year 2030.

Energy Consumption and Supply

The final energy demands result in primary energy requirements. In between are the various stages of energy conversion, transport and distribution. The final energy demands of 22.8 TWyr/yr in the High and 14.5 TWyr/yr in the Low scenario by the year 2030 (see Table 2.2) result in primary energy requirements of 35.7 TWyr/yr and 22.4 TWyr/yr, respectively. Table 2.3 gives the resulting global primary energy supply in the two scenarios for the seven regions, and Table 2.4 the corresponding per capita primary energy consumption. In both scenarios the primary energy consumption increases more in the developing regions (IV, V, VI and VII) than in the already industrialized ones (I, II and III). Despite the continued population growth in the developing regions the per capita consumption growth rates are also higher than the global average increases (1.5 percent per year in the High and 0.6 percent per year in the Low scenario). Nevertheless, the question remains open whether the gap between the developed and developing regions can be substantially narrowed. The primary energy share of the developing regions (IV, V, VI and VII), as the percentage of the global total, increases from 14 percent in 1975 to 42 percent in the High scenario and 38 percent in the Low scenario by the year 2030, and the primary energy per capita approaches the 1975 levels of the Regions II and III only in Regions IV and VI in the High scenario by 2030.

We have mentioned that one of the central features of the two scenarios is the quantitative balancing of energy demand and supply. Let us now consider how the primary energy requirements are met by different energy sources. Table 2.5 shows the energy supply of different primary energy sources in the two scenarios. The emerging pattern of primary energy supply confirms the dominating role of hydrocarbons also in the future. Especially large is the increase in coal use followed by a larger use of gas, although a strong reliance on oil is maintained by a steady increase of oil consumption in all scenarios. In terms of

Table 2.3. Two Supply Scenarios, Primary Energy by Region, 1975 to 2030 (TWyr/yr)

Region	1975	High Scenario 2000	High Scenario 2030	Low Scenario 2000	Low Scenario 2030
I (NA)	2.65	3.89	6.02	3.31	4.37
II (SU/EE)	1.84	3.69	7.33	3.31	5.00
III (WE/JANZ)	2.26	4.29	7.14	3.39	4.54
IV (LA)	0.34	1.34	3.68	0.97	2.31
V (Af/SEA)	0.33	1.43	4.65	1.07	2.66
VI (ME/NAF)	0.13	0.77	2.38	0.56	1.23
VII (C/CPA)	0.46	1.44	4.45	0.98	2.29
World[b]	8.21[a]	16.84	35.65	13.59	22.39

[a] Includes 0.21 TWyr/yr of bunkers--fuel used in international shipments of fuel.

[b] Columns may not sum to totals because of rounding.

Table 2.4. Primary Energy Consumption Per Capita, 2030 (kWyr/yr,cap)

Region	Base Year 1975	High Scenario	Low Scenario
I (NA)	11.2	19.1	13.9
II (SU/EE)	5.1	15.3	10.4
III (WE/JANZ)	4.0	9.3	5.9
IV (LA)	1.1	4.6	2.9
V (Af/SEA)	0.2	1.3	0.7
VI (ME/NAf)	0.9	6.7	3.5
VII (C/CPA)	0.5	2.6	1.3
World	2.0	4.5	2.8

Table 2.5. Two Supply Scenarios, Global Primary Energy by Source, 1975 to 2030 (TWyr/yr)

Primary Source[a]	Base Year 1975	High Scenario 2000	High Scenario 2030	Low Scenario 2000	Low Scenario 2030
Oil	3.62	5.89	6.83	4.75	5.02
Gas	1.51	3.11	5.97	2.53	3.47
Coal	2.26	4.94	11.98	3.92	6.45
Light water reactor	0.12	1.70	3.21	1.27	1.89
Fast breeder reactor	0	0.04	4.88	0.02	3.28
Hydroelectricity	0.50	0.83	1.46	0.83	1.46
Solar[b]	0	0.10	0.49	0.09	0.30
Other[c]	0.21	0.22	0.81	0.17	0.52
Total[d]	8.21	16.84	35.65	13.59	22.39

[a] Primary fuels production or primary fuels as inputs to conversion or refining processes; for example, coal used to make synthetic liquid fuel is counted in coal figures. (For definition of energy types, see Chapter 1, Figure 1.1.)

[b] Includes mostly "soft" solar--individual rooftop collectors; also small amounts of centralized solar electricity.

[c] "Other" includes biogas, geothermal, commercial wood use, as well as bunkers used for international shipments of fuels; for 2000 and 2030, bunkers are not estimated.

[d] Columns may not sum to totals because of rounding.

relative shares, however, oil use drops globally from 44 percent in 1975 to almost 19 percent by 2030 in the High scenario. This is possible because synthetic fuels produced from coal substitute oil. This also explains the relatively high consumption of coal, and it also stresses the principal role of liquid fuels in the future. In the Low scenario, oil's share of primary energy remains somewhat higher at a level of slightly more than 22 percent. In this scenario oil conservation and substitution is more limited primarily due to lower economic growth: Infrastructure and technological changes are harder to achieve and lower grade resources are harder to exploit.

In both scenarios natural gas and hydropower maintain their present market shares, although clearly their absolute consumption levels increase. The high demand for synthetic fuels, that are necessary to replace oil, reduces the availability of coal as a primary fuel for electricity generation. Thus, in order to relieve the coal supply for other purposes, nuclear energy is devoted exclusively to electricity generation in both scenarios. The nuclear share of about 23 percent of all primary energy in the two scenarios is significant but it nevertheless shows that the complete transition to alternative sources of energy was not possible in the two scenarios. It turns out that the time horizon of the study was one of the major constraints in the implementation of the sustainable energy system in the two scenarios. Fast breeder reactors (FBR) are not introduced before the year 2000, and mainly due to the capacity build-up constraints they could not acquire a higher share in energy supply in spite of their efficient use of resources. Similarly, the full deployment of solar power also lies beyond the year 2030. Within the next 50 years the main uses of solar energy foreseen in the scenarios are of local character, such as space heating.

The picture that evolves from the supply scenarios shows that it is possible to meet the accounted final energy demand by a balanced and regionally consistent primary energy supply mix. It shows that it will not be easy but that it could be done, although the transition to alternative energy sources cannot be fully realized within the next 50 years. Nuclear and solar energy indeed do relieve the fossil fuels supply requirements in general, especially those fossil fuels used for electricity generation, but they cannot diminish the continued liquid fuels demand that still had to be supplied by oil and synthetic fuels from coal. Figures 2.5 and 2.6 show the difference in the structure of primary energy supply between the developed and developing parts of the world. A large asymmetry can be seen in the supply of nuclear energy, synthetic fuels and oil. While the developed regions can substitute some of the current oil supplies by increased use of nuclear energy and synthetic fuels production from coal, the developing regions continue to rely on oil as a major source of liquid fuels.

The Implications for Western Europe

The Global Study indicates that it is possible to master the transition by 2030 to an energy system that will later, beyond 2030, allow energy supply from effectively infinite

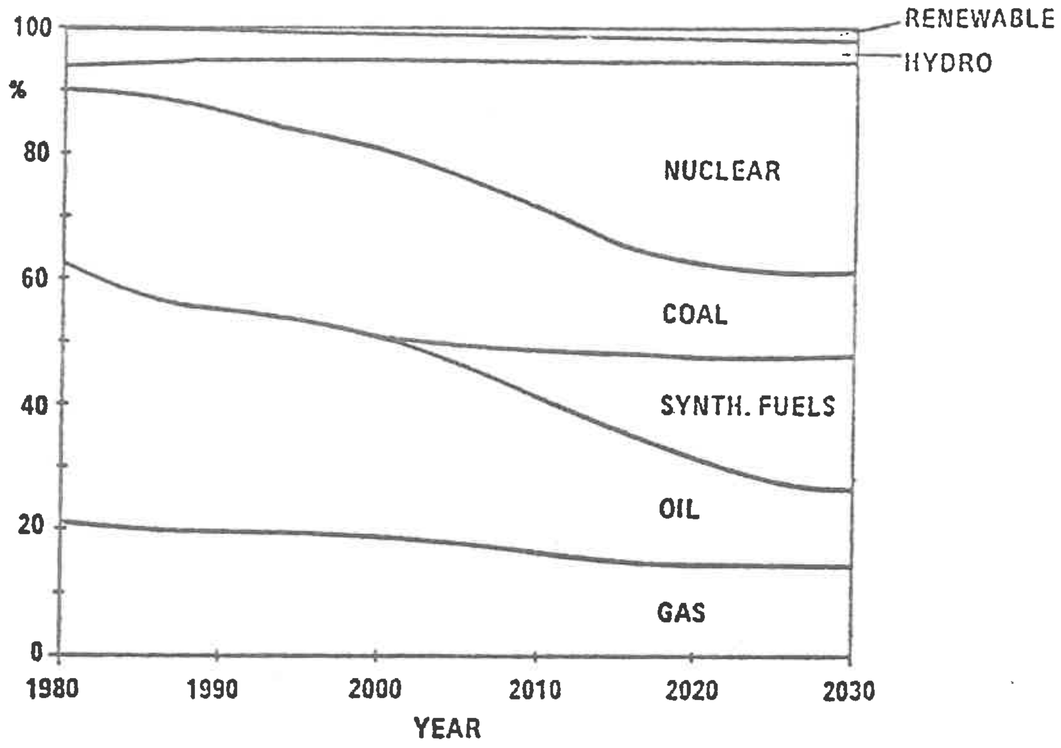


Figure 2.5. Developed regions (I-III), High scenario. Primary energy or equivalent in percent.

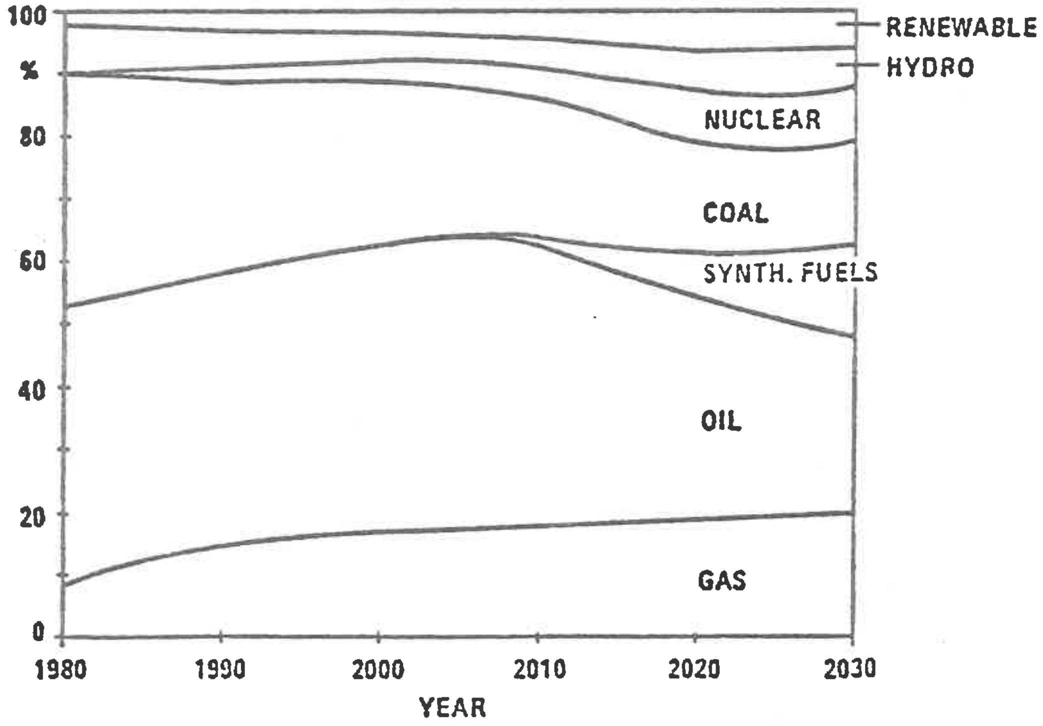


Figure 2.6. Developing regions (IV-VII), High scenario. Primary energy or equivalent in percent.

energy sources, such as solar and nuclear energy. This transition, however, is superimposed by another transition between now and 2030: a transition from relatively clean and inexpensive to "dirtier" and more expensive energy sources. During this time period the interdependence of the global energy system is crucial. A given country or region, that is in a position to use energy more effectively than others in providing desired commodities, is more likely to acquire the required share of globally available energy. Moreover, such flexibility of developed countries translates either into an alleviation or aggravation of the energy problem in developing countries, depending on whether such a given industrialized country or region requires less or more of the world-wide energy supply.

The Western European countries, as a subset of Region III, are unique in this respect. They have developed, industrialized market economies, but due to the lack of endogenous energy resources they meet most of their energy needs through imports. In 1975 more than one half of the primary energy requirements were supplied by oil coming mainly from Gulf states. Also most of the coal and natural gas consumed originated abroad. If this heavy dependence of Region III on imported fossil resources were to be maintained beyond 2030, the amounts available to the developing parts of the world would be even more limited. Figure 2.7 gives the oil trade patterns between the regions. The insufficient supply of liquid fuels is especially critical in Region III and has to be balanced by oil imports. Region VI continues to be the world's largest oil exporter. Thus oil trade is important in alleviating resource scarcity especially in Regions III and V. If the oil production rates should be lower, serious shortages of liquid fuels could be expected. The consequences would be drastic, but the possibility must be considered. Other developed regions, i.e. Regions I and II, are not in such a drastic position since their endogenous production could cover the demand by 2030. Therefore, large oil import requirements of Region III are in direct competition with oil import needs of the developing world, especially Region V. If we add to this the fact that most of the natural gas used in Region III is also imported, primarily from Region II, the picture is completed: By 2030, Region III is still

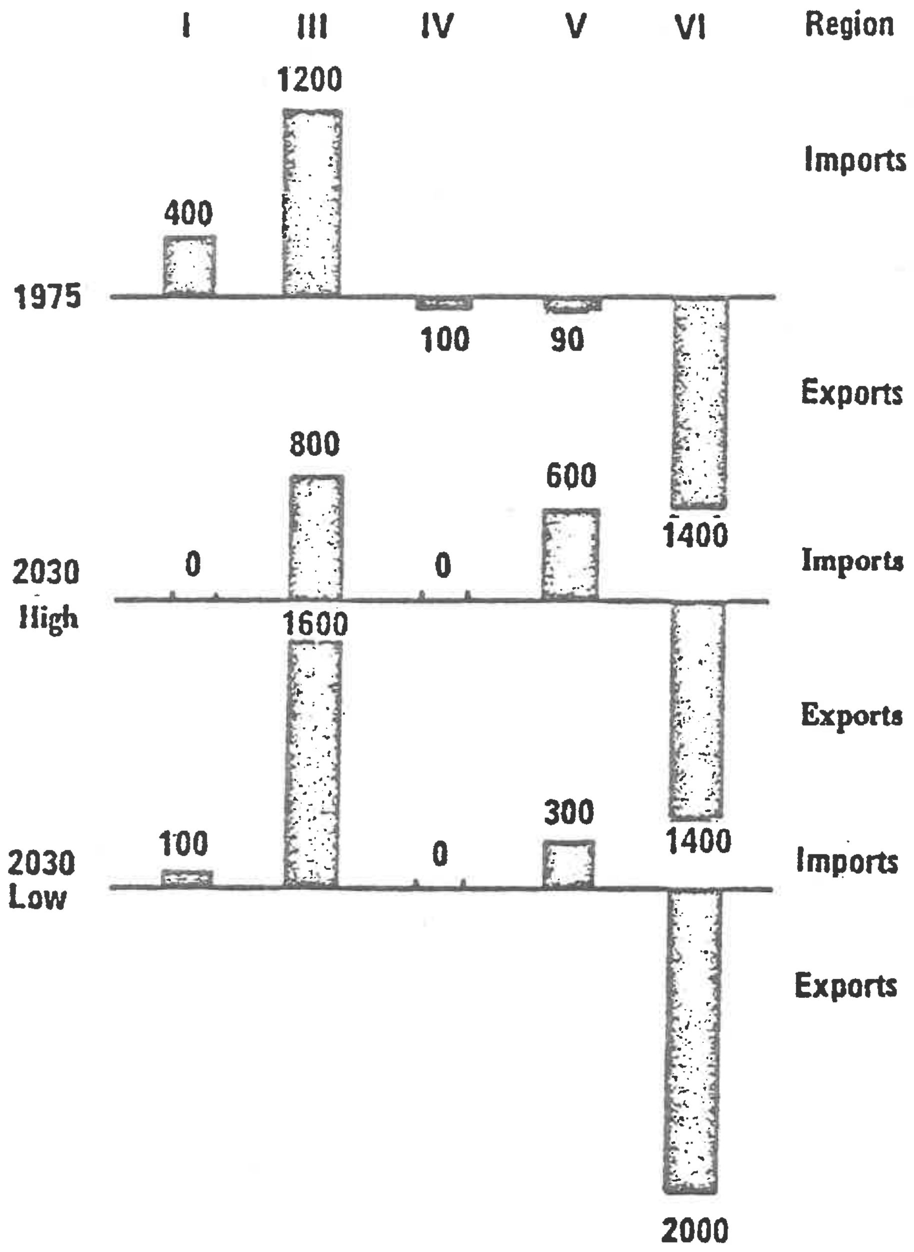


Figure 2.7. Oil trading regions, 1975 and 2030 (GWyr/yr).

extremely dependent on imports of fossil fuels, that are also required elsewhere.

In the Solar Study for Western Europe, therefore, one of the primary goals was to complete the transition to sustainable energy systems after 2030, and completely diminish oil and other fossil energy import requirements by the end of the next century. The achievement of this transition not only adds an important flexibility to European energy supply by reducing the vulnerability to possible shortages of fossil fuels on the world markets, but also allows greater use of available fossil energy in developing parts of the world.

3. BASIC CHARACTERISTICS AND ASSUMPTIONS

Global and Internal Consistency

We have seen that the IIASA Global Study identifies the energy outlook up to the year 2030, and also outlines the major changes necessary to achieve the transition to a sustainable energy system thereafter. Our objective in the Solar Study for Western Europe was to further investigate the possibility of such a transition, how to achieve it and still remain consistent with the global energy prospects. Thus, in order to observe the global consistency, we do not rely on energy options and potential solutions found infeasible in the Global Study. However, our objective, at the same time, is to investigate the amount of flexibility Western Europe could have in achieving this transition. We considered the complete transition away from fossil energy sources, and therefore our time horizon is much longer than that of the Global Study. By going to the year 2100, this transition is possible. We have stretched our imagination in specifying three extreme scenarios which still allow consistent energy systems, but do cause serious limitations on the overall economy. Each of them represents an all-out effort to implement one particular energy option: hard solar, soft solar and nuclear energy. Since each scenario is feasible as an energy system, together the scenarios also outline the limits to flexibility in implementing a sustainable energy future in Western Europe.

In the Solar Study we have chosen to be consistent with the economic growth of the Global Low scenario in testing the limits of the flexibility of the Western Europe energy outlook. This was necessary, since the Global Study showed that the economic growth of the High scenario alleviates some of the strain imposed in the Low scenario: The amount of sustainable energy supplied by 2030 is higher and the energy savings potential is also higher. Therefore, the use of the lower economic growth assumptions in the Solar Study puts an additional strain on the implementation of the extreme scenarios and further constrains the flexibility in the transition to a sustainable energy future. If higher economic growth is achieved as in the Global High scenario, then the transition would be easier to achieve. Our objective in that sense was not to be conservative in economic growth assumptions, but to explore a possible lower bound knowing that any additional growth would rather alleviate some of the strains than aggravate them. In addition, our results show that it is questionable whether a high economic growth is even possible with the Soft Solar scenario.

The Spatial Scope

The spatial scope of the Solar Study covers the whole of Europe, outside the COMECON countries and Asia Minor. We refer to this geographic area as Western Europe. 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 a 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. For example, the comparison of the GDP per capita level can serve to illustrate this point.

The seven world regions distinguished in the Global Study spanned a wide range with respect to the level of economic development: Using GDP per capita as an indicator, the lowest level was found for Region V (Africa and Southeast Asia) with 240$(1975)/cap, while the value for Region I (North America) is almost 30 times as high, namely 7050$(1975)/cap. For Region III (Western Europe, Japan, Oceania and South Africa) the average level of GDP per capita in 1975 was 4260$(1975)/cap; Figure 3.1 shows that for Western Europe alone it was 4400$(1975)/cap, but with a range of almost a factor of 10 between Turkey and Switzerland (with 900 and 8500$(1975)/cap, respectively).

In order to account for some of these and other differences between the various parts of Western Europe, the countries were grouped into three more homogeneous areas which we label North, Central and South Europe. Table 3.1 lists the individual countries

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*Strictly speaking, Cyprus and Iceland are also European countries but they were not treated explicitly.

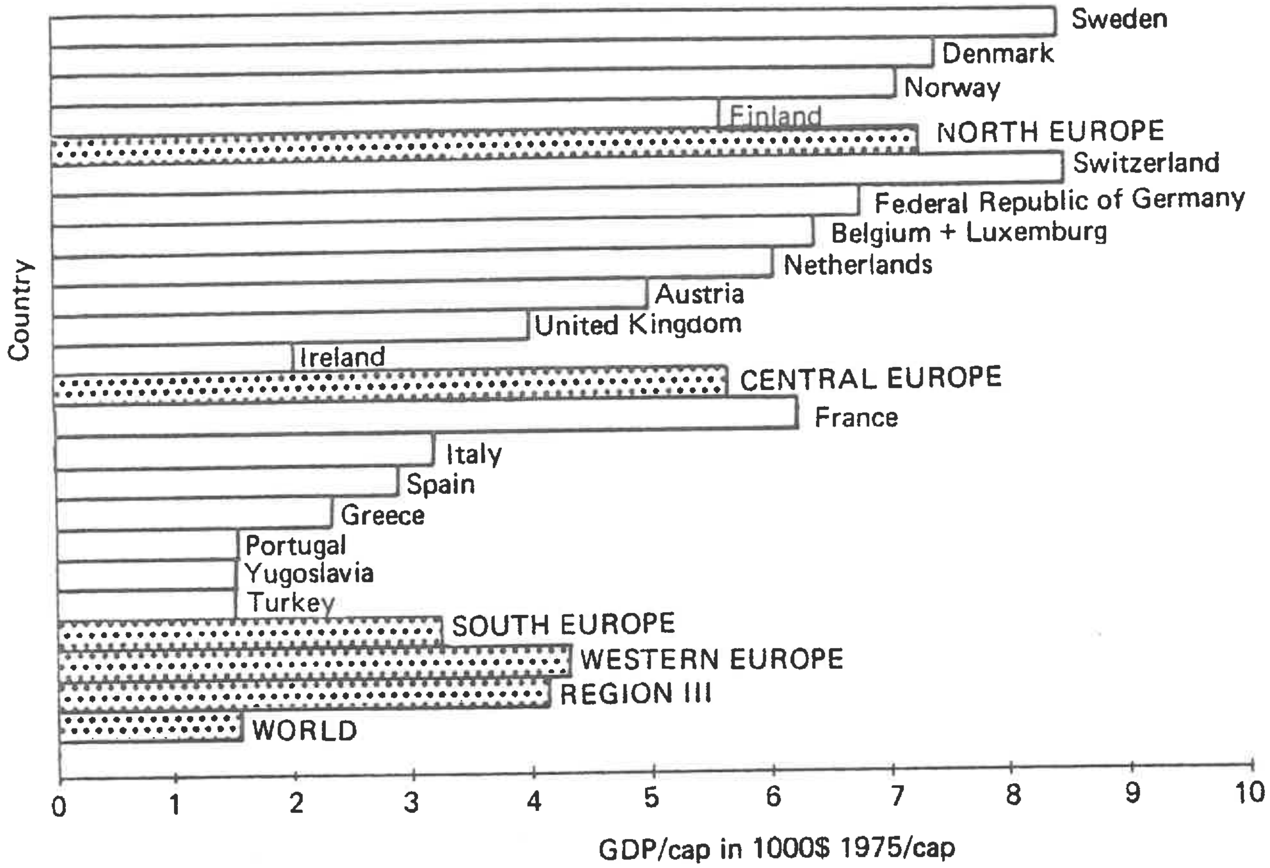

Figure 3.1. GDP per capita in Western European countries, 1975.

Table 3.1. Western Europe

South	Central	North
France	Austria	Denmark
Greece	Belgium	Finland
Italy	Federal Republic of Germany	Norway
Portugal	Ireland	Sweden
Spain	Luxemburg	
Turkey	Netherlands	
Yugoslavia	Switzerland	
	United Kingdom	

according to these three areas and Figure 3.2 shows the corresponding geographic divisions. 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. A potential disadvantage is the fact that this division of Western Europe does not correspond to the political groupings as they exist today, but in this study we do not consider political issues explicitly, although we recognize and mention them where appropriate.

The Temporal Scope

The temporal frame of the Solar Study is longer than 100 years, or more than twice as long as the time frame of the Global Study. There are many reasons for this choice. The main reason, however, is to allow for enough time to complete the transition away from fossil energy sources. We have seen that 50 years is not long enough to completely capture this transition. Judging from the past and the results of the Global Study, about 100 years are required to complete such a transition to new energy sources, thus such a long time horizon. Enough time must pass to make the fundamental infrastructural changes possible. For example, 120 years ago fuel wood was the major source of energy in Europe and it took about 50 years before coal replaced it and another 40 years passed before coal was substituted by oil and natural gas. Extrapolating into the future we arrive at the year 2100 as an a priori target date for full substitution of fossil by nuclear and solar energy. In fact, we will see later in the report that the results of the Solar Study show that the transition could be achieved somewhat earlier in the 2070s.

Population, GDP and Energy Consumption

Basic assumptions that determine the structure of the energy system are the population and GDP growth. These together with a number of other salient assumptions and system constraints result in final energy demand. After all energy conversion and transport stages are considered in terms of various technologies and their constraints, the final energy demand results in the

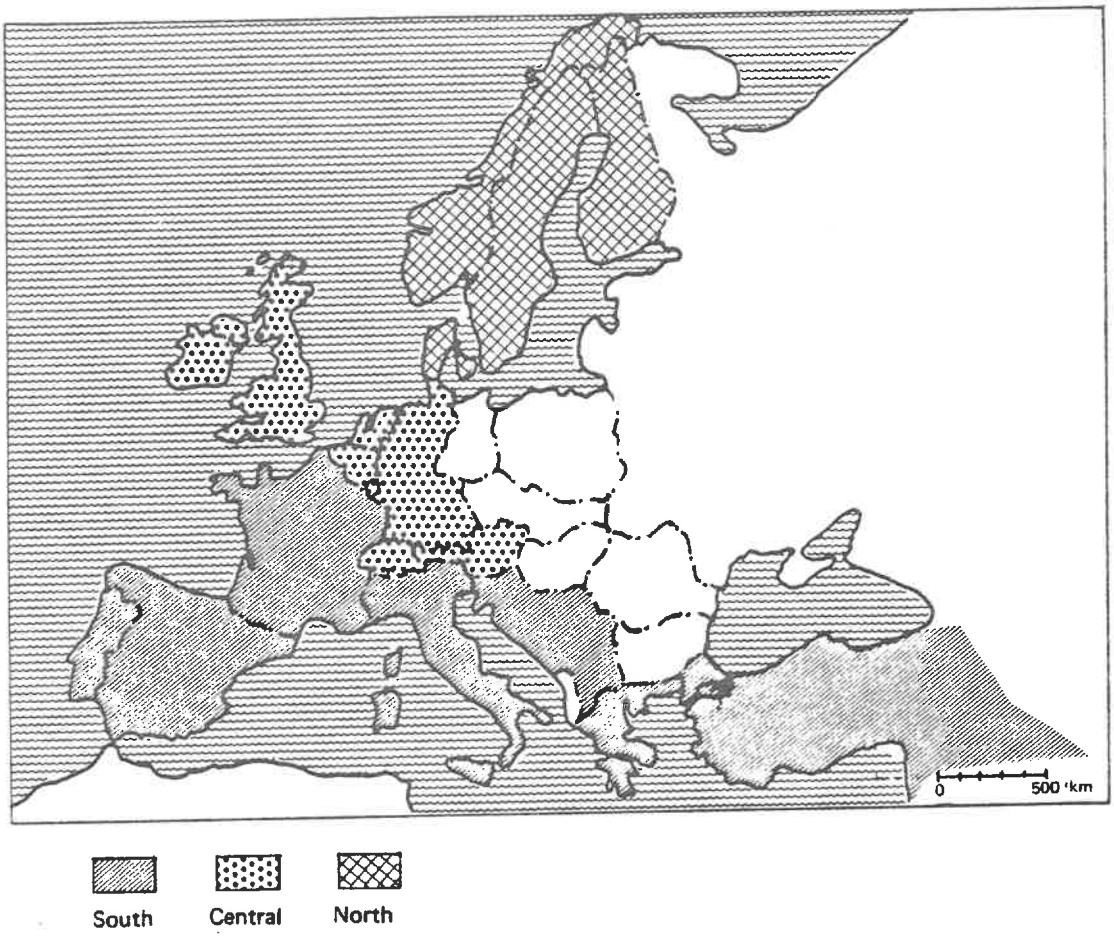

Figure 3.2. Western Europe.

required primary energy supply. Before considering the projected population and assumed GDP growth for Western Europe up to the year 2100, we will consider these important characteristics, relevant for the evaluation of the scenarios, as they exist today.

Table 3.2 gives a comparison of Western European countries with respect to selected indicators for 1975, the base year of the study, and the aggregate of these indicators for North, Central and South Europe, Region III and the World. These indicators are meant to characterize the relative importance of each country, its climate, its level of economic development and living standard, urban-rural settlement pattern and energy use level. Since most of these indicators (in addition to a number of other salient indicators) are also used in the scenarios, thus requiring an assessment of their future evolution, the wide range of values in this cross-country comparison is quite helpful.

In terms of its population Western Europe represents 72 percent of Region III and in terms of GDP 74 percent; its share of primary energy consumption of Region III is 67 percent. Thus, with respect to these three important indicators, Western Europe can be characterized as a rather homogeneous part of Region III.

However, Western Europe is much more densely populated than the rest of Region III. It represents only about 28 percent of the total area of Region III and its population density is therefore higher at about 90 cap/km^2 while Region III has on average only about 35 cap/km^2.

North Europe is the least populated with only 6 percent of the Western European population. The rest is distributed with 39 percent in Central and 55 percent in South Europe. Although there are large variations between the Western European countries in the level of development (indicated by GDP/cap level) the Northern countries are most developed with an average level higher than 7000$(1975)/cap, the Central European level is about 25 percent lower and the South European less than one half. Primary energy consumption per capita also shows this North-South trend as the GDP per capita levels do, but the difference is also large. From the total of 1.5 TWyr/yr consumed in Western Europe during

Table 3.2. Population, GDP, Energy Consumption, Areas and Solar Radiation of Western European Countries, 1975

Country	Population (10^6 people)	GDP (10^9 \$75)	GDP/capita (1000\$75/cap)	Primary Energy (GWyr/yr)	Energy/capita (kWyr/yr,cap)	Total Area[a] (1000 km²)	Population Density (cap/km²)	Energy Density (W/m²)	Degree Days	Population In Cities >50000 (%)	Population Rural (%)	Radiation City	Radiation Mean Solar Radiation (W/m²)
Denmark	5.0	37.1	7417	23.4	4.68	43.1	116	0.54	3480	28	33	Copenhagen	116
Finland	4.7	26.6	5652	24.1	5.12	337.0	14	0.07	5000	26	49		
Norway	4.2	29.8	7100	37.1	8.84	323.9	13	0.11	4400	33	34		
Sweden	8.3	70.1	8446	59.8	7.21	449.8	18	0.13	4200	48	19	Stockholm	123
North Europe	22.2	163.6	7368	144.4	6.51	1153.7	19	0.13	4245	36	31		
Austria	7.5	37.6	5011	30.4	4.05	83.9	89	0.36	3300	33	48	Vienna	124
Belgium	9.8	61.7	6301	53.4	5.45	30.5	321	1.75	3120	21	29		
FRG	61.7	418.4	6782	317.1	5.14	248.6	248	1.28	3230	47	19	Hamburg Munich	112 134
Ireland	3.1	8.0	2590	8.9	2.88	70.3	44	0.13	3230	na	48		
Luxemburg	0.4	2.3	6389	5.2	13.00	2.6	114	2.00	3120	na	na	Brussels	111
Netherlands	13.6	82.6	6072	76.6	5.63	41.2	330	1.86	3200	47	22		
Switzerland	6.5	55.1	8478	28.5	4.39	41.3	157	0.69	3000	45	42		
UK	56.4	228.8	4056	285.9	5.07	244.0	231	1.17	3200	na	23	London	103
Central Europe	159.0	894.4	5625	806.0	5.07	762.3	208	1.06	3203	43	24		
France	52.9	339.8	6423	212.7	4.02	544.0	97	0.39	2450	46	30	Paris Marseilles	129 179
Greece	8.9	20.5	2302	17.0	1.91	131.9	67	0.13	900	45	47	Athens	180
Italy	55.0	173.7	3158	167.8	3.05	301.3	183	0.56	1860	35	52	Genoa Naples Messina	167 192 203
Portugal	8.8	13.7	1562	9.5	1.08	92.1	96	0.10	900	16	74		
Spain	35.4	101.7	2874	77.9	2.20	504.8	70	0.15	1400	13	45	Madrid Barcelona	181 169
Turkey	39.9	35.8	898	26.3	0.66	780.6	51	0.03	1900	23	62		
Yugoslavia	21.3	33.1	1555	42.6	2.00	255.8	83	0.17	2600	28	61	Belgrade	154
South Europe	222.2	718.3	3233	553.8	2.49	2610.5	85	0.21	1929	39	48		
Western Europe	403.4	1776.3	4406	1504.2[b]	3.73	4526.5	89	0.33	2558	30	38		
Region III	560	2385	4259	2260	4.04	16000	35	0.14					
World	3946	6175.5	1565	8210	2.08	151000	26	0.05					

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[a] Total Area includes inhabitable land, polar regions, deserts, high mountain areas and similar grass lands and low productivity forests. Inhabitable land alone is only $9.5 \cdot 10^6 km^2$ for Region III and $80.3 \cdot 10^6 km^2$ for the World. The corresponding population and energy density numbers are 59 cap/km² and 0.24 W/m² for Region III and 49 cap/km² and 0.1 W/m² for the World.

[b] Primary energy consumption without biomass, with biomass 1530.5 GWyr/yr were consumed in 1975.

1975, 10 percent were consumed in North Europe, 53 percent in Central and 37 percent in South Europe. Energy consumption densities were the highest in Central Europe with an average of more than 1 W/m^2, but South and North Europe had averages of 0.2 and 0.13 W/m^2. Finally, the population densities are the lowest in North Europe with about 20 cap/km^2 (exception Denmark with 116 cap/km^2), South Europe has less than 100 cap/km^2 (exception Greece with 183 cap/km^2) and Central Europe has the highest densities with an average of more than 200 cap/km^2 (exception Ireland with 44 cap/km^2).

While the energy densities are the highest in Central Europe, the heating requirements are 25 percent lower in Central than in North Europe and another 30 percent lower in South Europe. On the other hand, the mean solar radiation (averaged over one year) is almost twice as large in the South than in the North. This is perhaps one of the most important indicators for the extent to which solar energy can be utilized. It has a crucial bearing on the investment costs in solar energy systems and land area requirements. The degree of urbanization of the population determines the extent to which energy generation and distribution systems have to be centralized in order to deliver the required energy density to the consumption centers.

Tables 3.3A and B show the structure of primary energy supply, Table 3.4 the import dependence with respect to each primary energy source, and Table 3.5 the structure of electricity production for Western Europe and its three divisions. The import dependence is highest in South Europe (73%) and North Europe (59%); in Central Europe it is only 44 percent due to the self-sufficiency with respect to coal and gas which together cover almost 50 percent of the primary energy consumption. The import dependence with respect to oil is 96 percent in Central and South Europe; in North Europe the figure is 86 percent. Hydropower use is extensive in North Europe, where it covers 73 percent of electricity production, and also in South Europe, where 33 percent of the electricity are generated from hydropower. In Central Europe, 53 percent of electricity is generated from coal. Oil is not extensively used for electricity generation except in South Europe, where it supplies 34 percent of the electricity consumed.

Table 3.3A. Primary Energy Consumption by Source, Western Europe, 1975 (GWyr/yr)

	Europe			
Source	North	Central	South	Western
Coal	9.4	242.6	84.7	338.4
Oil	82.0	369.1	353.9	803.2
Gas	0.9	149.1	50.4	201.6
Nuclear	4.0	20.3	10.0	36.8
Hydropower	48.1	24.8	55.3	124.1
Biomass	4.7	1.9	19.7	26.3
Total	149.4	807.9	573.5	1530.5
Share (%)	9.8	52.8	37.4	100.0

Table 3.3B. Primary Energy Shares by Source, Western Europe, 1975 (%)

	Europe			
Source	North	Central	South	Western
Coal	6.3	30.0	14.8	22.1
Oil	55.0	45.7	61.7	52.5
Gas	0.6	18.5	8.8	13.2
Nuclear	2.7	2.5	1.7	2.4
Hydropower	32.2	3.1	9.6	8.1
Biomass	3.2	0.2	3.4	1.7
Total	100.0	100.0	100.0	100.0

Table 3.4. Primary Energy Import Dependence by Source, Western Europe, 1975 (%)[a]

	Europe			
Source	North	Central	South	Western
Coal	97	2	62	11
Oil	86	96	96	95
Gas	100	-5	47	8
Nuclear/Hydro	0	-3	3	0
Biomass	0	0	0	0
Total	59	44	73	53

a) Energy import dependence is calculated as a fraction of imported energy in total use of a given energy source. The total import dependence represents a fraction of total imported energy in total domestic energy use of all sources.

Table 3.5. Electricity Generation and Share by Energy Source, Western Europe, 1975 (%)

	Europe			
Source	North	Central	South	Western
Coal	7	13	21	36
Oil	13	15	34	19
Gas	1	12	6	10
(Fossil total)	(21)	(80)	(61)	(65)
Nuclear	6	9	6	8
Hydropower	73	11	33	27
Total	100	100	100	100
Share	14	51	35	100
Total (GW(e)yr/yr)	24	86	58	168

More details about final energy consumption are shown in Tables 3.6, 3.7 and 3.8*. In North Europe, electricity accounts for 20 percent of final energy consumption, compared to about 12 percent in Central and South Europe, due to the availability of hydropower. For Western Europe as a whole, the final consumption of fossil fuels is divided between thermal uses (industry, household and service sectors) and specific uses (motor fuel or feedstocks) in a ratio of about 2 to 1; in South Europe, motor fuels represent a larger share than in North and Central Europe due to the lower industrialization and the warmer climate.

Fuelwood use is insignificant in Central Europe. In North and South Europe it represents a 5 percent addition to the commercial final energy use. Assuming that it would be mainly used by households, and assuming an efficiency of about two-thirds relative to commercial fossil fuels, the contribution to useful energy consumption of households would be 9 percent and 11 percent in North and South Europe, respectively; with growing overall energy demand the share of such uses of fuel wood will certainly decline, especially in South Europe.

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*To recall the definitions: The difference between primary and secondary energy consumption consists of the conversion losses. The difference between secondary and final consists of transportation and distribution losses. Final energy is the energy purchased by the final consumers; it is sometimes also called "delivered energy".

Table 3.6. Final Energy Shares by Type, Western Europe, 1975 (%)

	Europe			
Type	North	Central	South	Western
Coal	4.9	12.3	8.5	10.1
Oil	69.9	54.0	64.5	59.5
Gas	1.6	22.0	12.1	16.4
Electricity	19.2	11.4	10.6	11.8
Biomass[a]	4.4	0.3	4.3	2.2
Total	100.0	100.0	100.0	100.0
Share	8.9	52.8	38.3	100.0
Total (GWyr/yr)	106.7	630.9	456.9	1194.5

[a] Biomass use refers mostly to fuel wood.

Table 3.7. Final Energy Shares by Sector, Western Europe, 1975 (%)

	Europe			
Sector	North	Central	South	Western
Transportation	19	18	22	19
Agric./Const./Man.[a]	44	46	49	47
Households/Services	37	36	29	34
Total	100	100	100	100
Share	9	53	38	100
Total (GWyr/yr)	106.7	630.9	456.9	1194.5

[a] Agriculture, Construction and Manufacturing.

Table 3.8. Final Energy Shares by Use, Western Europe, 1975 (%)

	Europe			
Use	North	Central	South	Western
Thermal	50	58	53	56
Coke	2	4	4	4
Feedstocks	6	7	7	7
Motor fuels	22	19	25	21
Electricity	20	12	11	12
Total	100	100	100	100
Share	9	53	38	100
Total (GWyr/yr)	106.7	630.9	456.9	1194.5

Table 3.9 shows the summary of the indicators that describe the characteristics of Western Europe, its divisions, and compares them with those for Region III and the World. The future evolution of these indicators will have the decisive influence on energy demand and use patterns. In particular, the population and GDP levels and their future evolution are two basic assumptions that are used in the scenarios, and next we will consider the assumptions made about the population and GDP growth up to the year 2100.

Table 3.9. Summary of Important Indicators for Scenarios, Western Europe, Region III and World, 1975

Region	Population (10^6 people)	GDP (10^9\$75)	Energy Primary (GWyr/yr)	Energy Final	Total Area ($10^6 km^2$)
North Europe	22	164	144	107	1.2
Central Europe	159	894	806	631	0.8
South Europe	222	718	554	457	2.6
Western Europe	403	1776	1504	1195	4.5
Region III	560	2385	2260	1590	16
World	3946	6176	8210	5840	151

Basic Scenario Assumptions: Population and GDP Projections

In the Solar Study the same population evolution was assumed as in the Global Study. The projections are described in Keyfitz (1979); beyond 2075, they were simply extrapolated using the trend during 2050-2075 implied by the projections. For North and Central Europe an increase of only 12 percent and 17 percent above the 1975 level is projected. Over such a long period this is almost equivalent to stationary population levels. In South Europe, however, the population would increase by 65 percent above the 1975 level, giving an average increase for Western Europe of 41 percent between 1975 and 2100.

Table 3.10 and Figure 3.3 show the Western European population growing to 570 million people by the end of the next century. Due to the differential growths between the south and north, the population share of North Europe would decrease from 6 percent in 1975 to 4 percent in 2100, while Central Europe would

Table 3.10. Population Projection (10^6 people)

Region	Base Year 1975	Projection 2000	2030	2060	2100[a]
North Europe	22	24	25	25	25
Central Europe	159	172	182	185	186
South Europe	222	282	331	353	359
Western Europe	403	478	538	563	570
Region III	560	680	767		
World	3946	6080	7976		

[a] Population for period 2075-2100 was extrapolated from the trend during 2050-2075.

SOURCE: Keyfitz (1979).

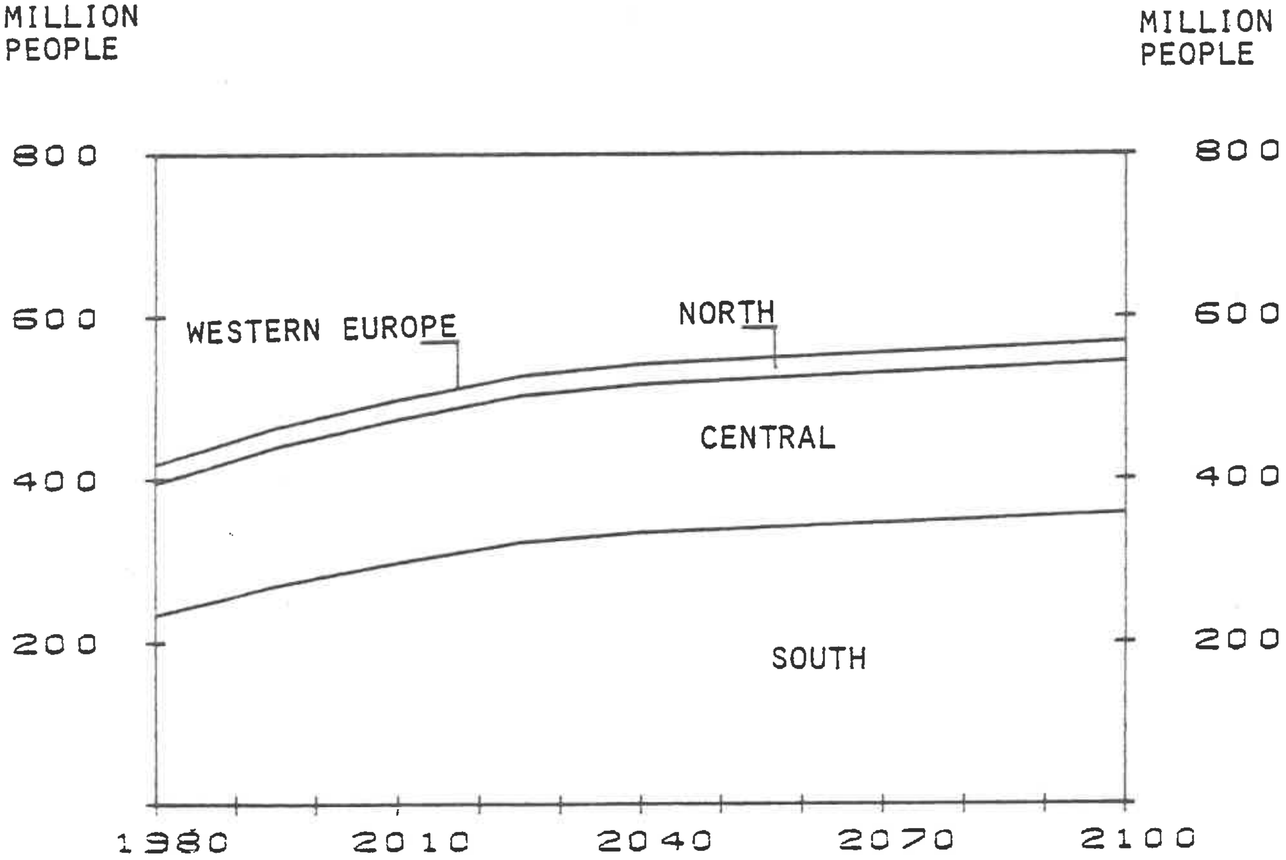

Figure 3.3. Population projection (10^6 people).

retain its relative position declining slightly from a 39 percent share to 33 percent over the same time period. South Europe, due to still growing population, would represent 63 percent of Western Europe in 2100 compared to 55 percent in 1975. Table 3.11 gives the population growth rates and shows that the whole of Western Europe would reach a stable population without additional growth by 2100. Finally, Figure 3.4 shows that the relative position of Western Europe within Region III would not change significantly over this long time period. Also other countries within Region III would achieve stable population levels.

For the future GDP growth in the Solar Study, the evolution assumed in the Global Study for the Region III Low scenario was taken as a guideline. In the post-war period, and especially during the 60s, Japan's share in the GDP of Region III (i.e., essentially OECD countries outside North America) was increasing rapidly--from 14 percent in 1963 to 22 percent in 1977, or 8 percentage points in 15 years, but the shift was slowing down in the latter half of the period. Due to Japan's heavy reliance on raw material imports and export possibilities, a further shift of only 4 percentage points was assumed, so that Western Europe's share of the GDP of Region III would decrease from presently 74 percent to 70 percent, the main shift occurring before the year 2000; after 2000, the growth rates of Japan would be almost identical to those of Western Europe.

Within Western Europe, South Europe increased its share by about 4 percentage points during the period 1963 to 1977. Because of the higher population growth in this subregion, the shift will probably continue, so that its share in the GDP of Western Europe could increase from presently 41 percent to 51 percent, but more steadily than in the case of Japan.

The projections were made--simplistically--by interpreting the GDP distribution between the subregions as a function of ln(GDP), calculating transition matrices from the data for the period 1963 to 1977, and keeping the estimated transition matrix constant throughout the projection period.

The values adopted for the scenarios are shown in Table 3.12, Figure 3.5, Table 3.13 and Figure 3.6. Tables 3.14 and 3.15 show the GDP per capita projections and growth rates and Table 3.16 summarizes the basic scenario assumptions.

Table 3.11. Historical and Projected Population Growth Rates (%/yr)

	Historical	Projected			
Region	1950-1975	1975-2000	2000-2030	2030-2060	2060-2100[a]
North Europe	0.7	0.3	0.1	0	0
Central Europe	0.7	0.3	0.2	0.1	0
South Europe	1.1	1.0	0.5	0.2	0
Western Europe	0.9	0.7	0.4	0.2	0
Region III	1.0	0.8	0.4		
World	1.9	1.7	0.9		

[a] Population growth for the period 2075-2100 was extrapolated from the trend during 2050-2075.

SOURCE: Keyfitz (1979).

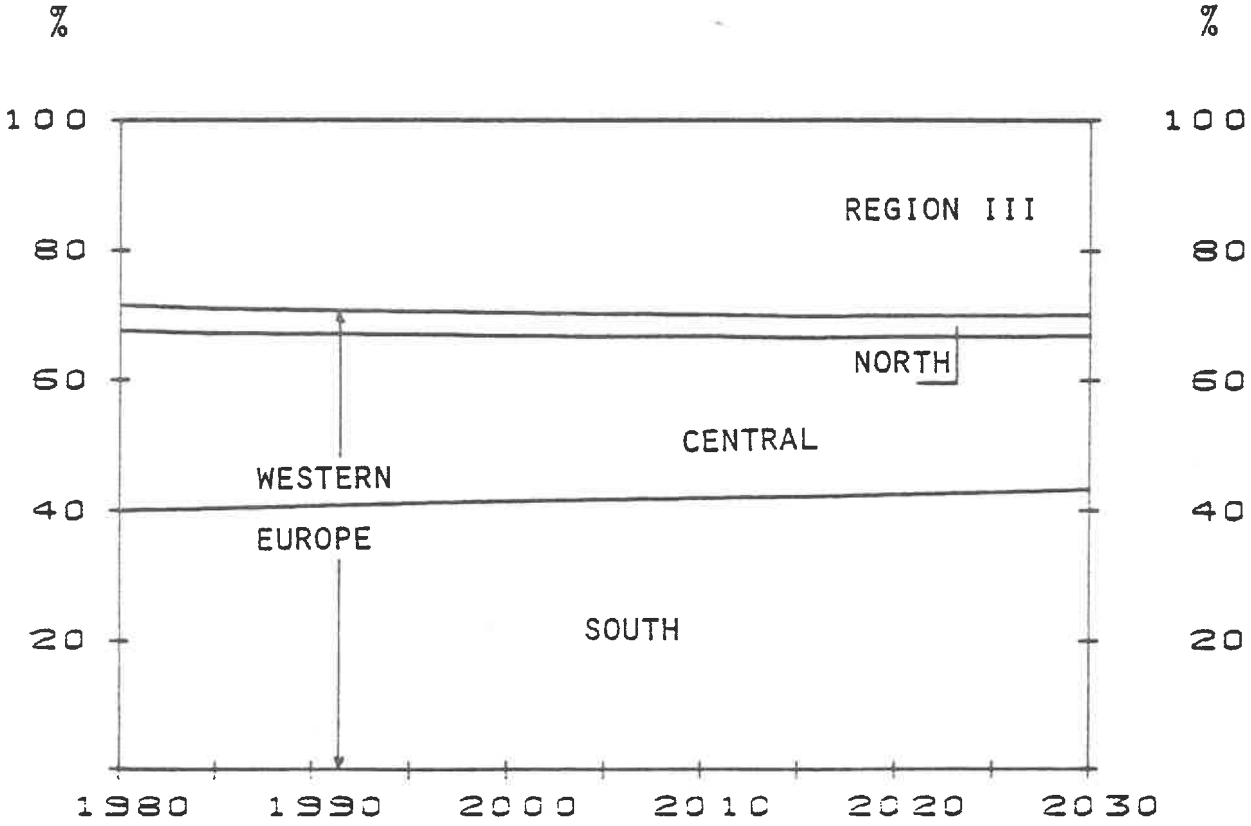

Figure 3.4. Population distribution in Region III (%).

Table 3.12. GDP Projection (10^{12}\$1975)

Region	Base Year	Projection			
	1975	2000	2030	2060	2100
North Europe	0.2	0.3	0.4	0.6	1.0
Central Europe	0.9	1.5	2.1	3.3	5.6
South Europe	0.7	1.4	2.2	3.8	6.8
Western Europe	1.8	3.2	4.7	7.7	13.4
Region III	2.4	4.5	6.8		
World	6.2	13.4	23.0		

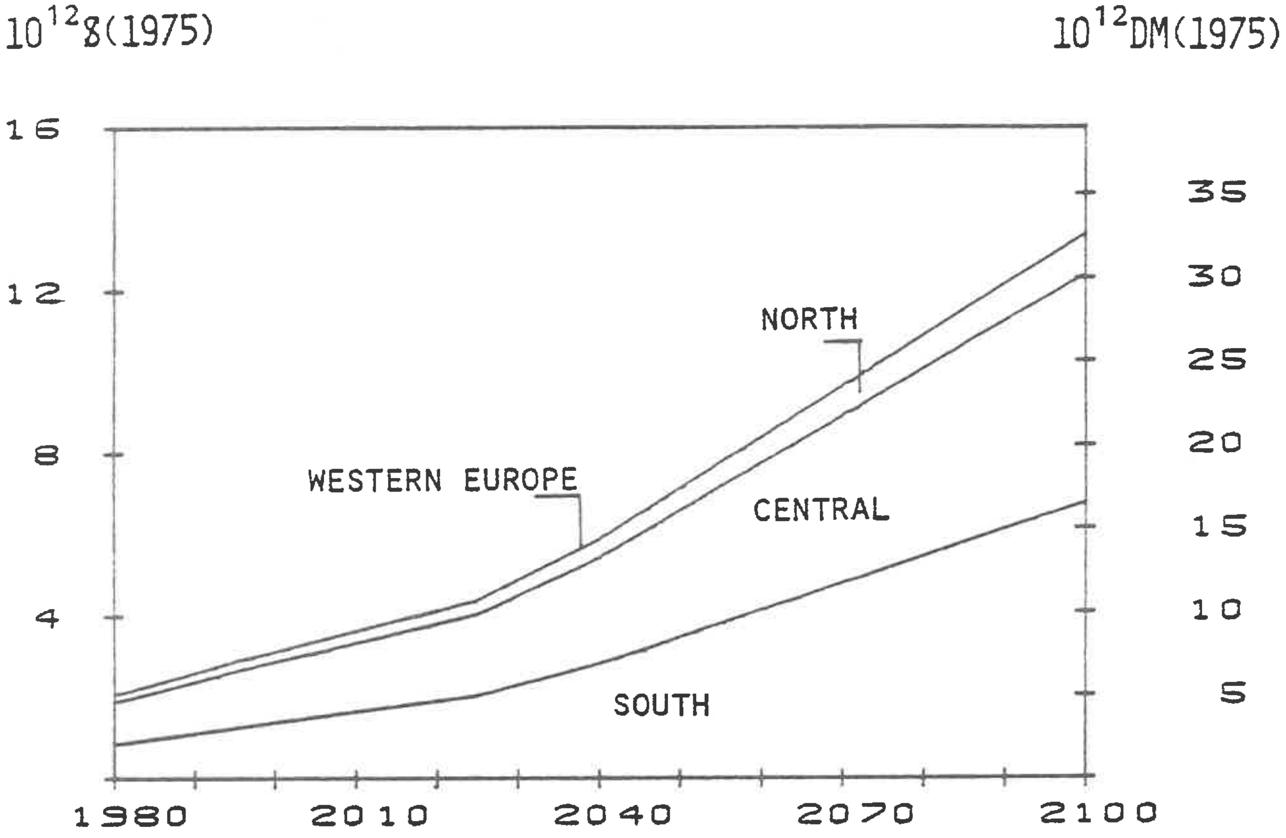

Figure 3.5. GDP projection (10^{12} \$1975).

Table 3.13. Historical and Projected GDP Growth Rates (%/yr)

Region	Historical 1950- 1975	Projected 1975- 2000	 2000- 2030	 2030- 2060	 2060- 2100
North Europe	5.2	1.9	1.1	1.5	1.3
Central Europe	4.2	2.1	1.1	1.5	1.3
South Europe	5.1	2.7	1.5	1.8	1.5
Western Europe	4.6	2.3	1.3	1.7	1.4
Region III[a]	5.1	2.5	1.4		
World[a]	5.0	3.1	1.8		

[a] Global Low scenario up to 2030.

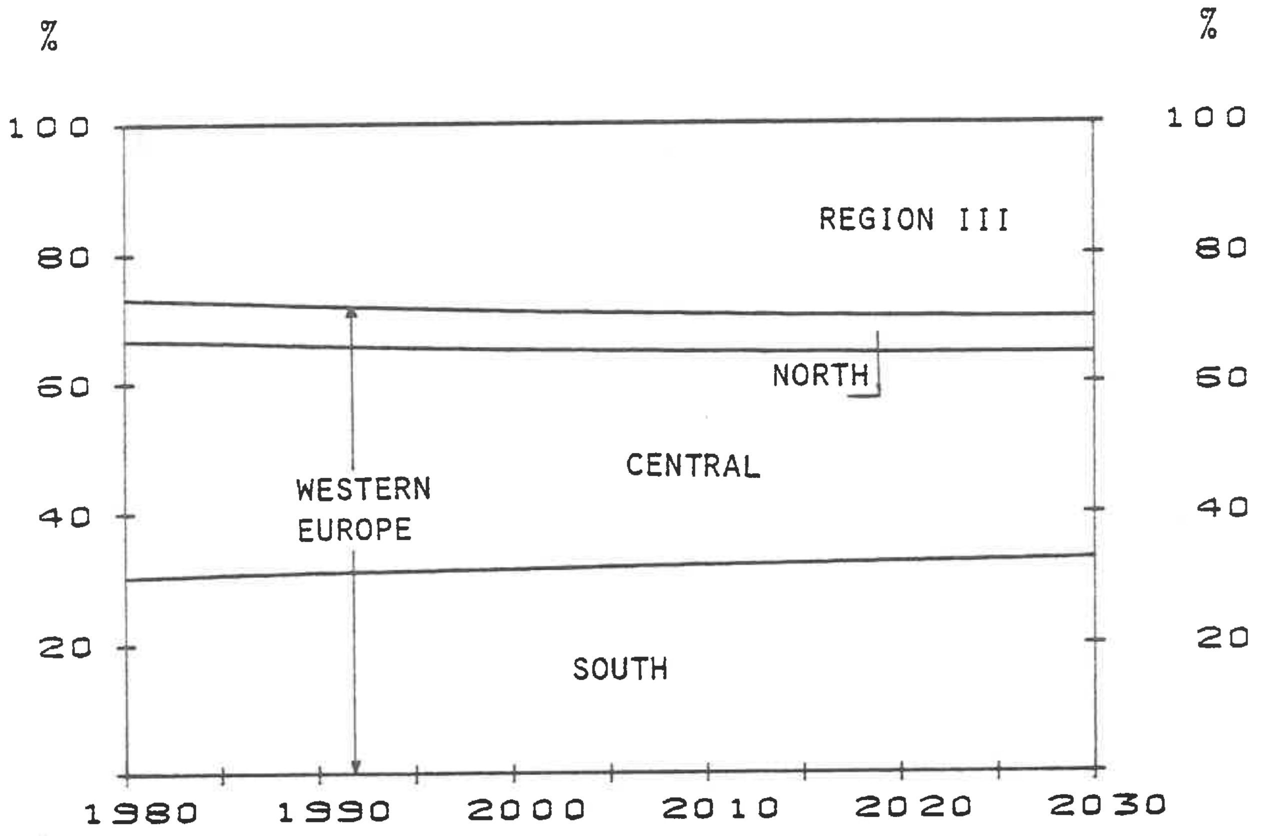

Figure 3.6. GDP distribution in Region III (%).

Table 3.14. GDP per Capita Projection (1000$75/cap)

Region	Base Year 1975	Projection 2000	2030	2060	2100
North Europe	7.4	11.1	14.9	23.3	39.8
Central Europe	5.6	8.7	11.6	17.8	30.3
South Europe	3.2	5.0	6.6	10.7	18.9
Western Europe	4.4	6.6	8.7	13.6	23.5
Region III[a]	4.3	6.5	8.5		
World[a]	1.6	2.2	2.8		

[a] Global Low scenario up to 2030.

Table 3.15. Historical and Projected GDP per Capita Growth Rates (%/yr)

Region	Historical 1950-1975	Projected 1975-2000	2000-2030	2030-2060	2060-2100
North Europe	4.5	1.6	1.0	1.5	1.3
Central Europe	3.5	1.7	1.0	1.5	1.3
South Europe	4.0	1.8	1.0	1.6	1.4
Western Europe	3.7	1.7	0.9	1.5	1.4
Region III[a]	4.0	1.7	0.9		
World[a]	3.1	1.3	0.9		

[a] Global Low scenario up to 2030.

Table 3.16. Summary of Assumptions: Average Annual Growth Rates of Population and GDP, 1975 to 2100 (%/yr)

Europe	Population	GDP	GDP/cap
North	0.1	1.4	1.3
Central	0.1	1.5	1.4
South	0.4	1.8	1.4
Western	0.3	1.6	1.3

Compared to the "short-term" post-war trends given in Table 3.15 these GDP growth rates seem extremely low. As long-term sustainable trends, however, the assumptions chosen for scenarios are probably not unrealistic, considering that the time span is longer than 100 years.

For comparison, Table 3.17 shows the GNP evolution in the United Kingdom and Sweden, respectively, over a period of similar length--135 years in the case of the UK, and 100 years in the case of Sweden. One reason for the more rapid growth rates in Sweden than in the UK might be that in the latter country the share of active population remained relatively stable, and the agricultural share of labor force was already low (20%) at the beginning of the period, i.e. 1841. By contrast, the share of active population in Sweden increased from 20 percent in 1875 to 45 percent at present, and the share of agricultural labor force declined from 65 percent in 1875 to 6 percent in 1975.

Except for the Southern countries, the growth potential from increasing labor force participation and from a shift away from agriculture to industry is already small, so that the future growth rates might be closer to those observed for the UK, where structural changes were only modest during the last century, because of the early start of industrialization. This example shows that the GDP growth rates projected for the Solar Study have a parallel in the Western European past over a similarly long time period.

Table 3.17. Historical Growth Rates of Population and GNP[a] for Sweden and the United Kingdom (%/yr)

Country	Period	Population	GNP	GNP/cap
Sweden	1875-1976	0.6	3.2	2.6
United Kingdom	1841-1976	0.8	1.9	1.2

a)GDP levels were available only for more recent years, for earlier periods GNP levels were used.

4. SUSTAINABLE ENERGY SCENARIOS FOR WESTERN EUROPE

Scenario Definitions

The assessment of the energy outlook for Western Europe over the time period reaching to the year 2100 is clearly to at least some degree speculative. It is also obvious that a completely comprehensive study of the future is impossible. We use scenarios which outline the structures and patterns of our image of a consistent future as means of reducing the task to a feasible effort in fulfilling the objective of the study.

Perhaps the two most important assumptions that we made in the study in order to achieve this feasibility, are that we consider only a surprise-free future and assume economic cooperation. We do not envisage any major catastrophes and we do not rely on breakthroughs of any kind unforeseen today. Political and social aspects of the scenarios, their implications and relevant considerations are not analyzed explicitly although they are considered. In particular, a large degree of cooperation, goodwill and free economic exchange within Western Europe and in the world is assumed.

The scenarios should be viewed as a quantitative and consistent framework that explicitly analyzes the consequences of the assumptions we made. They are neither prescriptions of the "best" possible future nor descriptions of projected "reality". They are constructions that allow the exploration of required changes and relevant constraints in achieving a sustainable energy future in Western Europe. Thus all numbers and quantitative assumptions and consequent analyses should be seen as means of describing qualitative features of the future.

Only one future is possible, but we intentionally consider three extreme scenarios: a future with as much hard solar energy as possible and analogously futures with as much soft solar and nuclear energy as possible. Together these scenarios outline a range of feasible futures. They certainly do not represent the absolute physical upper limits for these energy supply alternatives, but they do represent the conceivable limits to the utilization of these alternatives within the structure of the whole energy system.

Each of all these scenarios implies a different infrastructural change of the energy system during the next century. One of the most important of these changes is the degree of centralization in energy generation, conversion and distribution.

Energy Demand

All scenarios in the Solar Study are based on the same population and GDP growth rates described above. In spite of that, there are large differences between the scenarios on the demand side that are due to assumptions about life-style changes and energy use efficiency improvements. These result in two energy demand projections, a Higher and a Lower one. For example, the differences between the two demand projections are most dramatic with respect to process heat requirements, whereas they are not so great with respect to specific electricity, although they do exist.

The Lower demand projection is consistent with decentralized scenarios since the mostly local energy generation implies enormous life-style changes that could at the same time allow lower energy use at the same GDP level. However, it is obvious that the GDP as an index, although being the same quantity for both energy demand projections, does imply different economic structures that go along with different scenarios. In a similar way, the Higher energy demand projection is consistent with the centralized scenarios.

In general, we can state that different energy demand levels based on the same GDP assumptions will imply different economic evolutions of Western Europe. It is obvious that the energy demand is closely linked with material throughput in the economy. On the level of the whole economy, it is impossible to describe each specific economic activity separately in monetary flows, but they are usually used to capture the general interrelationships. As the economic structure and life-style change over time, the GDP index will actually measure different things. The typical basket of goods associated with the Low energy demand projection of the decentralized scenarios will be different from that one associated with the Higher demand of the centralized scenarios. Our energy demand analysis in the MEDEE-2 model captures these different material needs associated with the same GDP levels of different scenarios in physical terms and energy use efficiency improvements during the period under consideration.

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. Thus, the structure of energy supply and life-style patterns is closely linked in our analysis, although it is not possible to easily represent these structural changes on the aggregate level of the whole economy. In addition to population and GDP growth, driving forces for Lower energy demand are energy price increases. We will see that the centralized energy supply systems are in fact costlier. However, this link between energy prices and energy demand is not formalized in our study, although it is obvious that without higher energy prices significantly lower energy demand would be implausible (all other things being equal). On the other hand, when one goes so far into the future as was necessary in this study, due to large structural changes energy price elasticities become meaningless and cannot be used explicitly in the study. Our approach, as outlined above, was to account the specific energy needs in physical terms, in each sector of the economy, based on the population and GDP levels and their structure. On the supply side, the price elasticities are not used either; instead, energy production, conversion and distribution costs are used to implement a cost minimal energy system consistent with the specified structure and levels of energy demand.

Thus the implementation of each scenario can be divided into two distinct parts: first, the assessment of energy demand level and the associated activities in the whole economy, e.g., industry and transport, household and commercial sector changes that go with that energy demand level; and second, the structure of the energy supply system capable of delivering the demanded energy to the consumer. Methodologically we used the energy demand accounting model MEDEE-2 to assess the quantities of required useful and final energy and the energy supply model MESSAGE II to find an economically optimal mix of primary energy sources to deliver the required energy under relevant constraints.

Figure 4.1 illustrates this methodological approach. The MEDEE-2 model is used to assess energy demand structure and levels for each scenario starting from the GDP assumptions and population growth projections. The resulting useful energy demands by energy form are used then to determine the energy supply system in the MESSAGE II model. In addition, other models were used to assess in greater detail some of the more critical aspects of the scenarios, such as the overall macroeconomic implications of the scenarios (MACRO) and the investment requirements (IMPACT).

Energy Supply

In the centralized (Hard Solar and Nuclear) scenarios the demanded energy is eventually (by 2100) supplied from sustainable central solar or nuclear systems. This made it possible to assume that the energy use patterns in industry could remain practically unchanged over the time horizon of the study. In other words, the centralized sustainable energy systems would supply the industrial sector of the economy in an analogous manner as today so that drastic structural changes of this sector were not necessary. The efficiency of the private energy consumption is assumed to increase to the presently conceivable upper limits.

On the supply side, however, more drastic changes are assumed. It would be necessary to generate most of the needed energy in a large number of centrally located power plants. In the Hard Solar scenario most of these plants would be in South Europe, in the Nuclear scenario they would be not so far removed from consumption centers, but still most of them would probably be concentrated in a number of "energy parks". From these central power plants, large energy transportation and distribution networks are needed in order to reach the final consumer.

In the decentralized (Soft Solar) scenario the demanded energy is supplied to the largest degree possible by renewable and small-scale solar sources placed either directly on the side of the user, or as close as possible. The collocation of energy generation and conversion systems close to the user imposes other overall constraints on the structure of energy demand and supply than the centralized energy generation and conversion with long-distance energy transport and distribution. We have assumed

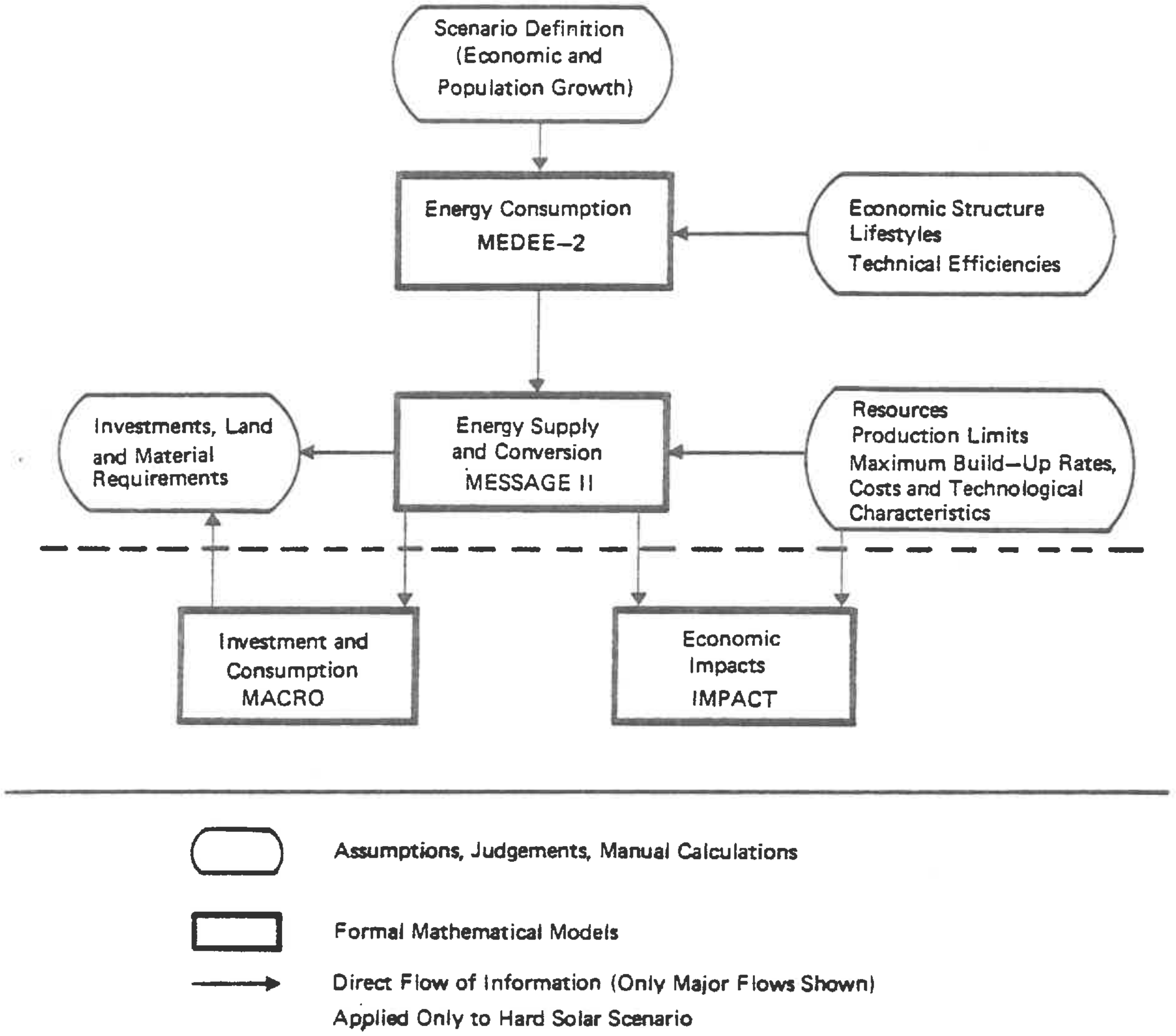

Figure 4.1. The set of energy models: A simplified representation.

that the decentralized energy systems would be coupled more easily with Lower energy demand and the centralized systems with the Higher one. In fact, the study shows that it is questionable whether the decentralized energy generation, even when taken to the maximum degree possible, could at all be feasible with Higher energy demand levels.

In each scenario the objective was to use the maximum feasible level of one type of energy supply system, 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" for energy supply. In the Nuclear scenario it consists of the burner 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 solar or hydropower plants.

The whole structure of the energy supply system is determined by implementing such a set of technologies which minimizes the overall cost of the supply system under constraints of build-up rates, resource depletion, etc. Thus, methodologically, 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". Following cost penalty structure is used--2.4 percent per year cost increase of fossil resources, natural uranium and nuclear system investment cost (except for the Nuclear scenario where nuclear technologies are the "reference system"). The case of the Soft Solar scenario is more complicated where cost subsidies are actually imposed within the "reference system" which will be discussed below.

We feel that such an approach leaves more flexibility to structure the energy supply system best suited under the given constraints. The other possible alternative--to limit the use of technologies by explicit constraints--was not preferred since it is too rigid and does not allow changes in the modeled supply system not foreseen by the researcher. Our approach actually resembles the current practice of imposing taxes and other penalties on "undesirable" alternatives.

Thus each scenario leads to the use of many technologies also including those not specified as desirable in the reference supply system. For example, in all scenarios biomass plays an important role as the source of liquid fuels that are necessary in order to replace oil in those markets where hydrocarbons are irreplaceable, e.g. feedstocks.

All of the scenarios lead to energy systems that do not rely on fossil energy sources. By the time the transition is completed to sustainable energy systems, some time during the 2070s, the delivered final energy would have completely different primary energy sources, but the forms of the final energy would be similar to the present ones. Figure 4.2 illustrates this transition from oil (refinery products) to methanol, natural gas to hydrogen and coal to biomass. Thus the types of final energy delivered are the same in all scenarios irrespective of the whole energy supply structure, but the mix and supply levels are different.

In the following we will describe how this final energy is supplied from the primary energy sources through various conversion steps and distribution networks while relying in each scenario to the maximum possible extent on the specified "reference energy system". In the Hard Solar scenario the emphasis is on the solar power plants installed in South Europe and long-distance energy transport networks to consumption centers. Here the Higher level of final energy demand can be supplied. In the Nuclear scenario, also centralized energy generation in mostly collocated nuclear power plants and energy transport networks are preferred. In the Soft Solar scenario local solar energy sources with as little energy transportation as possible constitute the "reference system". Here, however, only the Lower final energy demand can be reached. Table 4.1. illustrates the correspondence of the supply scenarios with the two energy demand projections. These are the three main scenarios that outline the possible extreme energy systems for Western Europe.

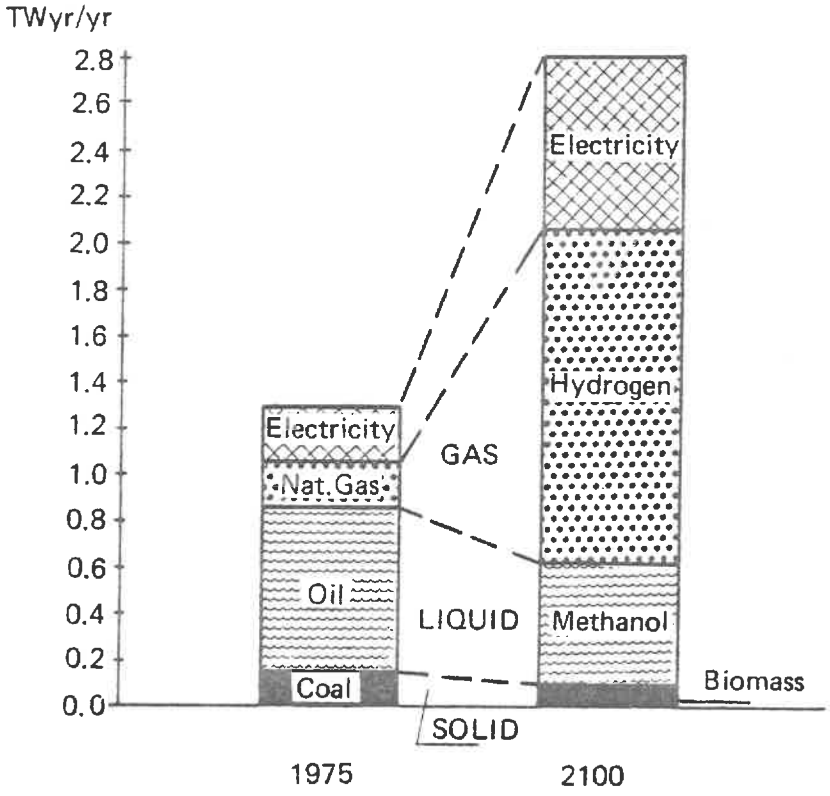

Figure 4.2. Final energy supply in the Hard Solar scenario, 1975 and 2100 (TWyr/yr).

Table 4.1. The Correspondence of Scenarios with the Energy Demand Projections

	Energy Demand Projection	
Scenario	Lower	Higher
Hard Solar		x
Soft Solar	x	
Nuclear		x

The Hard Solar Reference System

The solar insolation characteristics limit the construction of large solar power plants producing electricity or hydrogen to South Europe. Due to the much more favorable solar insolation in these areas the power plants have much higher capacity factors, high enough to offset large-scale energy transport losses and costs to the consumption centers in Central and North Europe.

Electricity is generated in Solar Thermal Electric Conversion (STEC) power plants in South Europe. Two basic types of STEC power plants are considered--with and without on-site thermal storage. The plants with thermal storage have a higher capacity factor and relieve some of the daily storage requirements from the rest of the energy supply system, but they are more expensive. The solar electricity generated in South Europe is transported to other areas via DC transmission links.

For additional daily storage needs the electricity can be stored in underground pumped hydro facilities, but due to capacity limitations, such facilities are not suitable for seasonal storage. To balance seasonal demand and supply variations electricity is not stored directly, but in the form of hydrogen after electrolysis of water. Hydrogen can be either consumed as such or it can be the source of electricity again when burned in fuel cells.

Hydrogen is also produced in South Europe along with electricity. Some of the STECs produce hydrogen either through thermolysis or on-site electrolysis. This hydrogen is transported to Central and North Europe by large hydrogen pipelines which also function as additional form of daily storage through pressure variations of about 10 percent.

All of the seasonal storage needs are thus implemented in the form of hydrogen, whether it is produced directly in the South in STECs or closer to consumption nodes by electrolysis from excess electricity. The hydrogen is then consumed as already mentioned, either directly or as electricity after it is burned in fuel cells, but it can also be used to produce methanol by blending it with biomass.

Biomass reaches the consumer also by three different conversion steps. Either it is supplied as solid fuel in the form of compressed pellets with energy densities equivalent to brown coal, blended with hydrogen into methanol, or used alone in an autothermal methanol production process.

Thus, altogether four forms of final energy reach the consumer: biomass as solid fuel, methanol as liquid fuel originating from biomass or biomass and hydrogen, hydrogen as gaseous fuel and electricity. On the primary energy side, all energy is produced in large STEC power plants located in South Europe and from large biomass plantations distributed throughout Europe.

The Soft Solar Reference System

The structure of a solar energy reference system that is based on decentralized energy generation on-site or in the vicinity of the final consumer is harder to define with any degree of generality. First of all there is a multitude of technologies which can be considered to be of a local character. Also, these technologies have a very wide range of energy production densities and absolute potentials. The generation densities play an important role, since in most cases and especially in more densely populated areas, the amount of land and total surface area available for energy generation is limited. In order to structure the problem, in this reference system we simply assume that generation systems that can be installed on-site, meaning either on the roof-top or in the immediate vicinity of the consumer, should have the highest preference. In order to achieve this we have imposed relative cost reductions (i.e. cost subsidies) on systems that are closer to the consumer. Thus on-site systems have a cost reduction of 60 percent, national or local level systems are 40 percent cheaper, and the costs of continental systems are not reduced*. This procedure then usually leads to the exhaustion of the potentials of technologies close to the user, starting from the most decentralized (on-site) systems, unless the reduced costs of more local systems exceed the costs of further removed generation systems. Thus, in effect these relative cost reductions are imposed in order to offset, to the extent still consistent with feasible potentials, the

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*For the specification of energy systems location with respect to the user see Table 7.1. in Chapter 7.

decreasing costs to scale of larger generation units. They show first of all the incurred additional cost to the whole economy that has to be paid in order to avoid large-scale systems and also to which extent one could use local energy sources even under such a favorable relative cost structure (that could possibly result from legislative measures such as higher taxes for larger energy systems and subsidies for decentralized, local ones).

This then also illustrates the earlier observation that the maximal reliance on decentralized solar systems "naturally" leads to the Lower energy demand projection although we do not explicitly consider prices. The relative cost penalties levied on large-scale energy generation systems in fact play a role of increased energy prices. They not only make even more drastic conservation and higher energy use efficiencies "economically" possible, but they also limit the availability of energy beyond the mere economic limits that would result from the cost structure without the imposed penalties and reductions.

The Nuclear Reference System

The whole energy conversion and distribution system in the Nuclear scenario is equivalent to that of the Hard Solar scenario. The major difference is in the sources of primary energy. The STECs in South Europe are replaced here by Light Water Reactors (LWR), Fast Breeder Reactors (FBR) and High Temperature Reactors (HTR) which are mostly collocated in "energy parks" which are a few hundred kilometers removed from consumption centers. In the case of the Hard Solar scenario the distances were much larger--2000 km or more. In addition some of the LWRs are located directly at the electricity grid nodes in the same way as they are today. Within the energy parks the LWRs and FBRs generate electricity and HTRs hydrogen by thermolysis. Here again biomass is the source of solid fuels and is also used to produce methanol.

By the 2070s the nuclear fuel cycle of all reactors is decoupled from additional natural uranium requirements. FBRs produce U^{233} from thorium in their blankets which is then "burned" in LWRs and HTRs.

In all three scenarios the energy supply is basically decoupled from limited resources. The Hard Solar scenario is based on continuous solar insolation as energy source and the renewable quantities of biomass. The Soft Solar scenario is based on renewable energy flows, such as wind power, local solar technologies and biomass, the Nuclear scenario on abundant resources of depleted natural uranium and thorium, and on renewable quantities of biomass.

5. ENERGY DEMAND AND END USE

Energy Demand Projections

The use of energy in industry, transportation, households and other sectors depends on a multitude of factors--most important among these are economic development and population growth. Among the other factors influencing energy use are climate, technological progress, regulations and taxes, energy and other prices, life-style changes, cultural characteristics, social and individual preferences, public perceptions, education, etc. The assumptions about the economic and population growth were given in Chapter 3. In this chapter we will discuss an evaluation procedure which allows the integration of the other factors influencing energy use together with population and economic growth assumptions in energy demand projections for Western Europe over the next 120 years. In fact, two sets of assumptions were used to result into two different energy demand projections, a Higher and a Lower one, both of them being based on the same economic and population growth assumptions. These energy demand projections should not be viewed as forecasts or predictions, they are conceptualizations of long-term energy demand prospects for Western Europe. Their value lies not in the specific numerical results, but rather in the structure of assumptions that had to be made in order to arrive at a consistent future energy demand.

The analyses of this chapter were aided by the use of the MEDEE-2 model which provides a detailed accounting framework for assessing the factors influencing energy use. The explicit links between MEDEE-2 and MESSAGE II occur at three possible levels: energy services, useful energy and final energy. Another important link, which is left to the judgment of the modeler and is not formalized in the sense of a mathematical model or a computer code, is between the assumptions made in assessing energy demand and the assumptions leading to a feasible (and optimal) energy supply strategy in each scenario. The Lower energy demand projection is consistent with decentralized energy supply and the Higher projection with a centralized one. This link between the demand and supply models is extremely important for the interpretation of the projections.

Clearly, it is beneficial if the same productive process or service can be accomplished with relatively fewer energy inputs (all other things being equal). With continually rising energy costs and their resultant economic and other burdens, energy saving is more than important--it is essential. However, in our scenarios more intensive energy saving must be achieved in decentralized supply strategies at the same level of GDP and population growth. This leads to the Lower energy demand level and means that although drastic overall energy saving is required in all scenarios, the Lower energy demand level can only be achieved through significant life-style changes that go beyond simple improvements in efficiencies of energy use in the production process and in providing services.

The demanded energy services can be expressed in terms of total vehicle-kilometers that have to be traveled by a given mode of transportation, or in demanded kilowatt-hours of electricity in manufacturing, or in kilowatt-hours of useful low-temperature heat required in the housing sector. This example illustrates that the energy demand is divided into categories depending on the type of required energy source. In some cases these services can be provided by only one kind of final energy, for example with liquid motor fuels or specific electricity uses. In other cases, an energy service such as space heating could be provided by many energy forms. In MEDEE-2 only the demand for such energy service categories is evaluated, while the choice of the best energy form for meeting a given service demand is determined within the overall scenario specifications in the energy supply model MESSAGE II (see Figure 4.1).

Let us recall the difference between energy services, useful energy and final energy. Final energy is the actual energy supplied to use, such as electricity for a house or gasoline for a car. The useful energy is the actual use derived from final energy, such as a switched-on light bulb or a moving car. Energy services are a well-lit room or travel by car.

Thus the energy demand projections are specified in terms of useful and final energy: useful energy for those demand categories where a number of final energy forms (usually each with different efficiencies) could provide a given service, and final energy for those demand categories where only one specific form of final energy can provide the service (e.g. feedstocks). The architecture of the supply system as determined by MESSAGE II specifies how all these demands are to be met.

In addressing the question of the less formalized links between the energy demand and supply we have actually alluded to this issue of differentiation between the energy service demand components and the actual structure of energy supply. In an energy supply system with emphasis on local and decentralized energy generation and conversion we are not likely to encounter a high demand for space heating with liquid fuels and most likely we can expect extensive insulation of buildings. We would also expect to find smaller shares of airplane transportation of goods and people. These kinds of issues go beyond the demanded quantities of one or the other form of energy, but profoundly influence the implied social structure, life-styles and a host of other aspects of everyday life. These, however, are not formalized in the models, but we have attempted to make consistent and equivalent assumptions for both the supply and the demand side.

An alternative to our approach would be to make energy demand projections on the basis of energy elasticities alone. In this approach the energy demand is related to economic and other price variables by elasticities which are determined on the basis of historical data or by an assumption. The attractiveness of this approach, especially in the short to medium-run projections, is its simplicity. On the other hand, as we mentioned in the previous chapter, when one goes so far into the future as was necessary in this study, due to the structural and life-style changes energy price elasticities become meaningless and cannot be used explicitly in the study. In view of the requirements of a less formalized judgmental link between energy demand and supply in our analysis, that extends beyond the formal link between the quantities of supplied and demanded energy, there is a more fundamental shortcoming of the demand-elasticity approach: namely, no insight is gained on how and where energy conservation and improvements of efficiencies may occur. Even at a detailed level of disaggregation no insight is gained as to physical parameter changes which are very helpful for the configuration of the appropriate supply strategy and for judging whether scenario projections are reasonable. We, nonetheless, do use energy elasticities for the interpretation of our scenarios, although we rely on the detailed accounting framework in generating the demand projections.

Energy Demand Components

The principal energy demand components, assessed by the accounting framework of MEDEE-2, serve as inputs for the energy supply model MESSAGE II (see Figure 4.1). Other assumptions made about the energy demand components are used on a judgmental basis to aid the structuring of the energy supply system in MESSAGE II so as to be consistent with the overall scenario characteristics that were briefly outlined in the previous chapter. We will return again to a detailed analysis of these scenarios in the following chapters.

The analytical approach embodied in MEDEE-2 calls for a detailed specification of the overall economic growth projections from Chapter 3. In particular, a sectoral breakdown of GDP is necessary in order to incorporate the factors influencing energy use, including anticipated changes in the investment and consumption shares of the GDP, in the mix of manufacturing activities, expected demographic changes, perceived changes in life-styles and so on. Such a disaggregation of GDP and the specification of anticipated future developments is not an easy task. The historical data are usually not available on such a level of disaggregation for longer time periods.

Thus the energy use accounting framework is implemented essentially as a process of estimating large numbers of detailed parameters most of which are influenced directly or indirectly by the specified GDP projections.

As the first step, besides the evolution of total GDP, the growth rates of various sectors have to be projected for each of the three parts of Western Europe; and besides the total population growth, also other demographic factors have to be assessed. Table 5.1 gives the specified sectoral GDP break-down for the three parts of Western Europe and Table 5.2 the most important

Table 5.1. GDP Sectoral Shares[a] Assumptions (% of GDP)
Two Energy Demand Levels for Western Europe and Region III of the IIASA Global Low Scenario

Region	Base Year 1975			Projection 2030			Projection 2100		
	Agric.	Energy Constr. Manuf.	Transp. Housing Serv.	Agric.	Energy Constr. Manuf.	Transp. Housing Serv.	Agric.	Energy Constr. Manuf.	Transp. Housing Serv.
Higher Demand Level									
North Europe	6.4	36.9	56.7	5.0	35.0	60.0	4.2	34.0	61.8
Central Europe	3.1	42.7	54.2	3.0	40.0	57.0	2.9	38.6	58.5
South Europe	8.2	37.9	53.9	5.0	39.0	56.0	3.4	39.5	57.1
Lower Demand Level									
North Europe	6.4	36.9	56.7	5.0	35.0	60.0	4.2	34.0	61.8
Central Europe	3.1	42.7	54.2	3.0	39.6	57.4	2.0	38.0	60.0
South Europe	8.2	37.9	53.9	6.3	37.7	56.0	6.0	34.0	60.0
Global Low Scenario									
Region III	5.8	45.7	48.5	3.0	41.0	55.0			

[a] GDP projections are given in Table 3.12.

Table 5.2. Demographic Assumptions for the Higher and Lower Demand Levels for Western Europe and Region III of the two IIASA Global Scenarios

	Base Year			Projection								
	1975			2000			2030			2100		
Region	Pers.	Pop.[a]	Eco.[b]	Pers.	Pop.[a]	Eco.[b]	Pers.	Pop.[a]	Eco.[b]	Pers.	Pop.[a]	Eco.[b]
North Europe	2.7	36	47	2.5	41	49	2.3	43	49	2.0	47	50
Central Europe	2.9	43	44	2.7	47	47	2.5	49	49	2.1	51	50
South Europe	3.2	39	31	2.9	46	43	2.7	48	46	2.0	52	47
Region III	3.0	49	45	2.7	52	50	2.6	55	52			

Pers. ... Persons per household
Pop. ... Population in cities > 50 000 (%)
Eco. ... Economically active population (%)

[a] Large cities with populations of more than 50 000 persons

[b] Economically active population (labor force) as a share of total population; population projection is given in Table 3.10.

demographic assumptions. For comparison the figures of the IIASA Global Low scenario are also given.

The demographic assumptions illustrate the expected trends. During the next 100 years stable population levels would be achieved throughout Western Europe (i.e., zero growth levels, see also Table 3.11), while at the same time urbanization is expected to increase together with a slightly increasing fraction of economically active population and with reductions in average family size (persons per household).

The projected sectoral GDP evolution (Table 5.1) shows that in addition to the same total GDP growth rates and the same demographic assumptions in the Higher and Lower energy demand projections, the differences are also modest with respect to the sectoral GDP evolution. Common features are significantly smaller shares of agriculture and somewhat larger shares of the service, household and transportation sectors and slightly lower shares of the construction and manufacturing sectors. The large differences between the two demand projections are due to the assumptions about life-style changes and energy-use efficiency improvements.

We will now discuss those assumptions and the resulting demand for energy services, useful and final energy. We state at this point, however, that especially the Lower demand projection is based on the expectation of a continuous increase of relative energy prices, which would motivate life-style changes and would accelerate efficiency improvements in energy use (including drastic conservation measures).

Agriculture and Construction Sectors

Motor fuel is the essential energy demand within agriculture and construction, while electricity and thermal energy uses are generally not very important. The intensity of energy use (per unit value added) has increased in agriculture in the past, but since 1973 this trend has reversed largely due to the higher prices for motor fuels. In the Higher demand projection it is assumed that no further changes in the energy intensity would take place, while in the Lower demand projection it is assumed that the intensities would be reduced to roughly one half of the current levels, largely due to the drastic life-style changes and drastic energy conservation measures. Table 5.3 gives the assumed values for motor fuels, specific electricity and thermal use intensities in the agriculture sector.

Initially most of these savings are expected to come from better insulation in greenhouses and storage buildings, lower temperature levels for crop drying and improved efficiency of electric and diesel prime movers (e.g. motors and tractors). In the long run the savings are expected to be achieved from new cultivation methods that could, for example, integrate separate tasks into one run of the tractor or allow a shift away from fertilization intensive agricultural patterns. The fuel demand is projected in terms of the amount of diesel that would be required if there were no alternative energy forms. The shift to new motor fuels (e.g. hydrogen), to new sources of electricity and thermal energy is modeled explicitly in the supply strategies that will be described in the following chapters.

Table 5.4 gives the assumed energy intensities in the construction sector for the Lower demand projection. As in agriculture, no substantial energy use reductions were assumed for the Higher demand, while in the Lower demand up to one half of motor fuel could be "saved" per value added and about 10 percent of the thermal energy needs. These energy intensity reductions are assumed to be achieved in an equivalent way as in the agricultural sector. They are possible only if higher energy efficiencies and new methods could be achieved during the next 120 years.

Manufacturing Sector

Industrial energy use is currently a major portion of the total consumption in the world, and in Western Europe roughly 50 percent of all final energy is consumed in industrial activities. In spite of the very long time horizon of over 100 years in the Solar Study, the scenarios do not incorporate major changes in energy consumption share of the industrial sector. In industrial production, energy is as a factor input an indispensable commodity, qualitatively different from energy used for transportation and space heating. While it is possible to drastically reduce energy use in transportation and house heating, both

Table 5.3. Energy Intensities in the Agricultural Sector (kWh/$75)

	1975			2100, Lower Demand[a]		
Western Europe	Motor Fuels[b]	Specific Electricity[b]	Thermal Uses[c]	Motor Fuels[b]	Specific Electricity[b]	Thermal Uses[c]
North Europe	2.0	0.3	0.5	1.1	0.2	0.3
Central Europe	1.6	0.4	0.2	0.9	0.4	0.1
South Europe	1.8	0.1	0.2	0.9	0.1	0.1

Table 5.4. Energy Intensities in the Construction Sector (kWh/$75)

	1975		2100, Lower Demand[a]	
Western Europe	Motor Fuels[b]	Specific Electricity[b]	Motor Fuels[b]	Specific Electricity[b]
North Europe	0.6	0.1	0.4	0.1
Central Europe	0.6	0.1	0.3	0.1
South Europe	0.6	0.1	0.3	0.1

[a] Energy intensities in the Higher Demand are assumed not to change from 1975 values.

[b] Final energy intensity in Wyr/$75 value added.

[c] Useful energy intensity in Wyr/$75 value added.

through technological efficiency improvements and other conservation measures, in the industrial production process it can be achieved practically only through technological improvements. For example, the amount of energy used in steel production depends mainly on the type of steel production process used and the output level, but the efficiency cannot be reduced infinitely--in the end it is limited by the laws of thermodynamics. Within our accounting framework, the industrial energy use is projected in the same way as the energy use of the agriculture and construction sectors, in terms of the product of the value added and the energy intensiveness.

Manufacturing industries (excluding energy producers) are classified into three subsectors, namely into industries producing predominantly basic materials, machinery and equipment, and consumption goods. The first subsector includes mining and manufacturing of primary metals, building materials, basic chemicals, but excludes energy sources such as coal, oil and gas. The third subsector includes only non-durable goods such as food, textiles and clothes.

Table 5.5 gives the projected shares of manufacturing in the total GDP (GDP growth rates were given in Table 3.13) and the shares of the three manufacturing subsectors in the total manufacturing value added. A common feature are the higher shares of machinery and equipment sector in both demand projections. All together, however, the assumed structural changes in manufacturing are not large. Thus, the future energy demand for manufacturing would be largely determined by the projected intensities of energy use. The energy intensity coefficients reflect both the technological patterns of production processes and the production mix in each subsector.

The mining and manufacturing of basic materials is characterized by a high energy demand per unit of output, both for electricity and thermal uses. The thermal energy demand of basic metal and building material industries is mostly in the high-temperature range (e.g., in furnaces), while the chemical and paper industries have a high demand for steam. The other two manufacturing subsectors have a relatively modest energy intensity: The machinery and equipment subsector's thermal energy

Table 5.5. Assumed Distribution of Manufacturing Activities in GDP (%)

	Base Year				Projection							
	1975				2030				2100			
Western Europe	Tot. Man.[a]	Bas. Mat.[b]	Mach. Equ.[c]	Cons. Gds.[d]	Tot. Man.[a]	Bas. Mat.[b]	Mach. Equ.[c]	Cons. Gds.[d]	Tot. Man.[a]	Bas. Mat.[b]	Mach. Equ.[c]	Cons. Gds.[d]
Higher Demand												
North	24.8	37.6	38.1	24.4	23.4	36.3	40.2	23.5	22.6	35.6	41.4	23.0
Central	31.6	35.6	40.2	24.2	28.3	33.5	43.5	23.0	26.6	31.4	45.2	22.4
South	26.2	34.1	33.0	32.9	27.4	31.4	34.7	33.9	27.9	30.0	35.6	34.4
Lower Demand												
North	24.8	37.6	38.1	24.4	23.4	34.3	42.2	23.5	22.6	30.0	48.0	22.0
Central	31.6	35.6	40.2	24.2	25.3	31.5	45.3	23.2	22.0	28.0	49.0	23.0
South	26.2	34.1	33.0	32.2	23.5	31.4	35.7	34.9	21.0	28.0	38.0	36.0

a) Total manufacturing (% of GDP).

b) Manufacturing of basic materials (% of total manufacturing value added).

c) Manufacturing of machinery and equipment (% of total manufacturing value added).

d) Manufacturing of (non-durable) consumer goods (% of total manufacturing value added).

demand is in the medium to high-temperature range (e.g. for metal processing), while the non-durable goods industries have a high demand for steam and hot water. In the last two subsectors space heating is also of importance.

The energy intensiveness is specified in Table 5.6 for the two main types of energy use in manufacturing: specific uses of electricity and useful thermal energy which can be provided by various energy forms (e.g., fossil fuels and hydrogen). The uses of coke and feedstocks are accounted for separately (see Tables 5.9A and B).

Table 5.6 shows that the relative decreases in energy intensiveness are very large, in the range of 30 to 60 percent in the Higher demand projection and 50 to 80 percent in the Lower one. Yet the part of this relative decrease that is due to structural changes is modest ranging up to a maximum of 8 percent.

Due to the large share of industry in total energy use, these differences in energy intensity of manufacturing contribute most dramatically to the differences in the overall energy consumption between the Higher and the Lower demand projections. In particular, the differences in the resulting useful thermal energy requirements (process heat) are large. Table 5.7 gives the process heat requirements for the two demand projections, and Table 5.8 the specific electricity requirements. The overall growth rate of thermal energy needs is 1.1 percent per year in the Higher and 0.2 in the Lower demand projection. The implied useful energy-GDP elasticities for process heat are 0.7 and 0.1, respectively. This is a dramatic difference and implies extremely large reductions in thermal energy needs, especially in the Lower demand projection. They imply fundamental changes and restructuring in manufacturing, including maximal utilization of waste heat from high-temperature processes for other production processes, which operate at lower temperatures, and also shifts to integrated production avoiding cooling and reheating in separate production steps. This implies a lower flexibility in product-range and location of production facilities. The following example illustrates this point. Continuous steel casting offers large energy savings, but it is only possible with a sufficient demand for products of the same size and

Table 5.6. Energy Intensity[a] in the Manufacturing Sector

Western Europe	Base Year 1975 Energy Intensity (kWh/$75)	Projection 2100 Energy Intensity (kWh/$75)	Relative Decrease (%)	Decrease Due to Structural Change (%)
Specific Electricity Uses (Final Energy)				
North Europe	2.5	(1.4-1.0)	(44-61)	(2-6)
Central Europe	1.1	(0.6-0.5)	(41-55)	(4-8)
South Europe	1.3	(1.0-0.7)	(26-61)	6
Thermal Uses (Useful Energy)				
North Europe	3.0	(1.0-0.6)	(67-79)	(1-4)
Central Europe	3.6	(1.6-0.6)	(56-83)	3
South Europe	3.9	(2.5-0.9)	(36-76)	(6-3)

[a] Values in parentheses: first value for Higher and second for Lower Demand projections.

Table 5.7. Process Heat[a] Requirements in Manufacturing (Useful Energy in GWyr/yr)

	Base	Projection			
	Year	Higher Demand		Lower Demand	
Europe	1975	2030	2100	2030	2100
North Europe	13.8	17.2	24.9	16.2	16.2
Central Europe	115.4	162.4	268.1	95.5	85.8
South Europe	82.9	229.1	546.0	143.0	153.1
Western Europe	212.1	408.7	839.0	254.7	255.1

a) Includes thermal uses for steam generation, furnace and space/water heating.

Table 5.8. Specific Electricity Requirements in Manufacturing (Final Energy in GWyr/yr)

	Base	Projection			
	Year	Higher Demand		Lower Demand	
Europe	1975	2030	2100	2030	2100
North Europe	11.5	19.5	38.0	15.2	26.2
Central Europe	32.5	58.9	117.3	46.5	76.0
South Europe	27.8	89.0	218.4	62.6	113.5
Western Europe	71.8	167.5	373.6	124.2	215.7

proportions. The need for higher standardization of industrial output and collocation of production would be only possible if production activity structure and life-style changes take place, settlement or transportation patterns change, and so on.

Tables 5.9A and B summarize the energy requirements in agriculture, construction and manufacturing. The demand categories have been divided into two groups; the first, mainly high and low temperature process heat, is expressed in terms of useful energy and can be supplied by almost any form of final energy. The second group represents specific final energy requirements that can be supplied only by a given form of final energy. For example, motor fuels stand for liquid energy carriers such as diesel and gasoline today and methanol and hydrogen in the future.

Transportation Sector

The structure of the transportation sector is similar in all three parts of Western Europe. The shares of freight transported by truck, train or barge are equivalent up to a few percent fluctuation. Similarly the distribution of passenger long-distance (intercity) and short-distance (urban) travel has close resemblance when viewed according to the mode of transportation. Thus the current differences in energy use of the transportation sector are largely influenced by the volume of transported people and goods. Together in Western Europe the transportation sector accounts for about 20 percent of the final energy use. Therefore, the future energy needs in transportation would have a significant influence on overall energy consumption, although the influence is not as drastic as that of the industrial sectors.

In addition to the future levels of the transportation of people and goods also structural changes in modes of transportation and transportation energy intensities (energy requirements per ton-kilometer or person-kilometer) are important determinants of energy use. Tables 5.10 and 5.11 give the assumed activity levels and structural changes in the modes of transporation. Lower energy use in freight transportation could be achieved in the Lower demand projection than in the Higher one, largely due to a strong shift away from truck to train transportation, a decrease

Table 5.9A. Energy Requirements in Agriculture, Construction and Manufacturing, Higher Demand Projection (GWyr/yr)

Use	Base Year	Projection			
	1975	2000	2030	2060	2100
Useful Energy					
Thermal Low	130.7	204.2	254.0	369.8	524.2
Thermal High	81.4	125.6	154.8	223.4	315.0
Final Energy					
Coke	42.1	49.5	53.3	66.4	83.9
Feedstocks	81.3	135.7	191.2	331.3	518.0
Motor Fuels	28.5	49.5	66.3	107.7	162.9
Electricity	77.1	123.6	167.5	255.8	374.0

Table 5.9B. Energy Requirements in Agriculture, Construction and Manufacturing, Lower Demand Projection (GWyr/yr)

Use	Base Year	Projection			
	1975	2000	2030	2060	2100
Useful Energy					
Thermal Low	130.7	160.8	158.9	159.6	160.5
Thermal High	81.4	99.1	96.1	95.5	94.6
Final Energy					
Coke	42.1	39.4	35.7	39.1	43.7
Feedstocks	81.3	104.8	119.6	161.0	216.3
Motor Fuel	28.5	45.9	54.3	75.9	104.8
Electricity	77.1	113.1	124.2	163.4	215.9

Table 5.10. Projected Activity Levels for the Transportation Sector (in %)

Western Europe	Base Year 1975	Projection Higher Demand 2100	Lower Demand 2100
Freight (10^9 ton-km)	1020.6	6412.2	4427.1
North Europe	11	8	9
Central Europe	40	31	31
South Europe	49	61	60
Passenger (10^9 person-km)	2567.7	8738.4	6756.0
North Europe	8	6	6
Central Europe	49	35	38
South Europe	43	59	56
Urban Transit Share of Passenger	22	24	24

Table 5.11. Assumed Structural[a] Changes in the Mode of Transportation (in %)

Western Europe	Base Year 1975	Projection Higher Demand 2100	Lower Demand 2100
Freight (10^9 ton-km)	1020.6	6412.2	4427.1
Truck	59	61	46
Train	27	26	42
steam	6	0	0
diesel	35	0	0
electric	59	100	100
Barge	14	13	12
Intercity Passenger (10^9 person-km)	1997.6	6599.5	5131.0
Car	65	56	52
Bus	15	10	10
Train	12	16	21
diesel	33	0	0
electric	66	100	100
Plane	8	18	17
Urban Passenger (10^9 person-km)	570.1	2138.9	1625.0
Car	88	49	49
Mass transit	12	51	51

a) Average changes for Western Europe, weighted according to the projected activity levels in the Transportation Sectors of North, Central and South Europe.

of truck transportation from the current share of 59 percent to 46 percent, and an increase of rail transportation from 27 to 42 percent. In the Higher demand level there is even a very small shift in the opposite direction. In both demand projections the structural changes in passenger transportation are very similar, mainly away from car to mass transportation systems.

The projections of passenger travel do not differ significantly: 8.7×10^{12} person-kilometers in the Higher demand level compared to 6.8×10^{12} person-kilometers in the Lower one. Compared to the current passenger transportation this is 1 percent per year and 0.8 percent per year growth rate. In per capita terms the increase is from 6400 person-kilometers per year at present to 15 400 and 11 900 person-kilometers per year by 2100, or a factor increase of 2.4 and 1.9. Compared with the assumed GDP per capita factor increase of 5.3 (see Table 3.14) the projected passenger travel in 2100 appears to be low indeed in both demand projections. This again illustrates that drastic life-style changes are necessary. The implied GDP elasticities are 0.6 and 0.4, which are low values. This is also evident from the very low share of plane travel, reaching less than 20 percent of intercity travel, and between 14 and 12 percent of the total passenger travel. Such low shares of the fast modes of transportation and slow growth of passenger transportation in general are against current trends. Considering that the constraining factors for (long-distance) travel are money and time, the assumed GDP growth rates could easily lead to higher travel demands. This is an especially critical assumption in the Lower demand level which projects a 23 percent decrease over the Higher demand.

To make all this possible, the following types of life-style and infrastructural changes in passenger transportation were assumed (see Table 5.11). In urban travel a slow shift away from individual to mass transit was assumed, from current car share of almost 90 percent to below 50 percent. Lower demand for urban transit implies increasingly more effective telecommunication systems, and a higher share of urban mass transportation implies very intensive city planning.

For long-distance travel (within Western Europe) much of the potential demand for travel by air would be substituted by high speed train links between the cities.

The energy use in transportation does not only depend on the distribution of different transportation modes and their respective usage, but also on the energy intensities per person-kilometer or ton-kilometer traveled by these means of transportation. The postulated declines of the energy intensities are a function of vehicle efficiency, capacity utilization, traffic flow, the type of fuel that is used and so on.

We have already mentioned that the specific energy demands that could be fulfilled by a number of final energy forms are explicitly modeled within the supply system. This is especially important in the transportation sector given our very long time horizon for the study. During the next 120 years,in addition to efficiency improvements,we also expect alternative energy forms to be used in transportation such as hydrogen powered cars. Thus only capacity utilization and traffic system aspects of energy intensiveness are considered here explicitly.

Tables 5.12A and B summarize the energy service requirements in transportation in terms of ton-kilometers for freight and vehicle-kilometers for passenger transportation (seat-kilometers for air travel). These estimates already include structural efficiency and utilization load improvements, but they do not include the fuel efficiency improvements.

Finally we have assessed the energy requirements, but in terms of currently used (fossil) fuels, shown in Table 5.13. In the following chapters we will return to this question and describe the actual energy requirements when the efficiency due to new (renewable) forms of fuels is also accounted for (see Table 7.5 in Chapter 7). In the Higher demand projection significant improvements on the vehicle efficiencies are postulated, but capacity utilization is assumed to increase only in airplanes by about 30 percent leaving the load factors of cars, trains and urban mass transit unchanged.

As can be seen from Table 5.13, the largest efficiency improvements are postulated for cars: In the Higher demand projection the fuel consumption per kilometer traveled is assumed to decrease by 52 percent and in the Low demand projection by 74 percent. This is a reduction from current average consumption of about 13 l/100 km for the whole fleet to about 6.1 and

Table 5.12A. Energy Services Requirements in Transportation, Higher Demand Projection

Use	Base Year	Projection			
	1975	2000	2030	2060	2100
Freight (10^9 ton-km)					
Truck	602.2	1003.7	1424.8	2478.3	3882.9
Train	275.6	446.9	627.5	1080.3	1683.9
Barge	142.8	224.6	315.2	542.5	845.4
Passenger (10^9 vehicle-km)					
Car	1073.5	1587.5	2074.2	2320.7	2649.3
Bus	21.6	37.3	51.1	57.4	65.7
Train	4.1	8.2	14.7	21.3	30.1
Plane (10^9 seat-km)	292.1	555.5	920.2	1178.4	1485.8

Table 5.12B. Energy Services Requirements in Transportation, Lower Demand Projection

Use	Base Year	Projection			
	1975	2000	2030	2060	2100
Freight (10^9 ton-km)					
Truck	602.2	824.8	1010.4	1449.7	2035.4
Train	275.6	424.7	656.8	1164.0	1840.3
Barge	142.8	196.7	258.4	384.0	551.4
Passenger (10^9 vehicle-km)					
Car	1073.5	1440.9	1549.1	1570.6	1606.1
Bus	21.6	27.4	29.6	31.3	32.5
Train	4.1	7.2	12.4	16.4	21.5
Plane (10^9 seat-km)	292.1	460.5	607.2	782.3	990.7

Table 5.13. Final Energy Intensity[a] in Transportation Using Fossil Liquid Fuels

Mode	1975	2100		
	Energy Intensity	Energy Intensity		Relative Decrease[b] (%)
		Higher Demand	Lower Demand	
Freight (Wyr/1000 ton-km)				
Truck	80	52	39	(35-51)
Train	33	20	16	(40-51)
Barge	40	26	26	(35-36)
Passenger (Wyr/100 vehicle-km)				
Car[c]	11	5	3	(52-74)
Bus	40	22	17	(45-57)
Train	265	207	158	(22-40)
Plane (Wyr/100 seat-km)	9	5	3	(43-65)

a) The assumptions are based on the use of fossil liquid fuels. Table 7.5 gives the conversion factors for other alternative fuels. Energy intensity numbers are averages for intercity and urban passenger traffic modes, they represent the assumptions for Central Europe.

b) Relative decrease in percent with respect to 1975 values. Values in parentheses: First value for Higher Demand and second for Lower Demand projection.

c) Corresponds to an average fleet fuel consumption of 13 l/100 km in 1975, 6.1 and 3.3 l/100 km in 2100 for the Higher and Lower Demand projections.

3.3 l/100 km. An average fuel consumption of 3.3 l/100 km implies that the whole car fleet in 2100 would consume on average no more fuel than the advanced prototypes built for research today. In addition it is assumed in the Low demand projection that the average capacity utilization of passenger cars would increase by 20 percent in intercity travel and by 150 percent in urban transit. The other major difference in efficiency assumptions between the two demand levels is for air travel, an efficiency improvement of 43 percent is assumed in the Higher and 65 percent in the Lower demand projection, while the capacity utilization improves in both by about 30 percent. For other modes of freight and passenger transportation efficiency improvements of roughly 30 to 40 percent are assumed throughout.

Households and Services Sector

The principal determinants of energy demand in households are first of all the number of dwellings and their type, such as apartments or single family houses. This not only influences the area that requires heating and lighting but also the insulation measures and the achievement of energy conservation. We have treated explicitly the following types of energy requirements: cooking, space heating, water heating, miscellaneous electrical needs for lighting, appliances and air conditioning. All of these specific energy needs (per dwelling per year) have been projected to decrease significantly due to better insulation measures, higher energy use efficiencies and new life-styles. In addition, by 2100 virtually all dwellings would be either replaced by post-1975 ones or retrofitted in order to achieve the comfort and energy efficiencies of post-1975 dwellings. Single room heating is assumed to be completely replaced by central heating throughout Western Europe. Today about 20 percent of the heating systems in North Europe are single room heating, whereas the shares are about 50 percent in Central Europe and about 75 percent in South Europe.

Table 5.14 gives the overall energy requirements per dwelling for the three areas of Western Europe and the projected values for 2100. The reductions are very large in the Low demand projection. For example the space heating demand would decrease per dwelling

Table 5.14. Projected Useful Energy Requirements in Households[a] (10^3kWh per dwelling per year)

	1975				2100, Projection							
					Higher Demand				Lower Demand			
Western Europe	Cooking	Spa. Heat.	Wat. Heat.	El. Appl.[b]	Cooking	Spa. Heat.	Wat. Heat.	El. Appl.[b]	Cooking	Spa. Heat.	Wat. Heat.	El. Appl.[b]
North Europe	0.7	16.0	2.5	2.0	0.5	9.5	3.2	5.0	0.2	3.8	2.7	2.2
Central Europe	0.7	13.4	2.7	1.8	0.5	9.1	3.4	5.8	0.2	3.4	2.3	2.0
South Europe	0.8	4.2	1.7	0.8	0.5	6.0	3.2	6.7	0.4	2.5	2.5	2.5

Spa. Heat. ... Space Heating
Wat. Heat. ... Water Heating
El. Appl. ... Electrical Appliances

[a] Average requirements for single family, apartment and single room dwellings. By 2100 the housing stock is completely replaced with post-1975 dwellings in whole Western Europe.

[b] Miscellaneous electrical appliances in households including air conditioning.

by 75 percent (40 percent in South Europe) in the Lower demand projection, and by little more than 30 percent (it actually increases in South Europe by 50 percent) in the Higher demand projection. The second large savings are achieved in the Lower demand projection with respect to specific electricity use. On the average for Western Europe the electricity needs per dwelling are projected to increase by a factor of 2.3 in the Lower demand and by a factor of 5.2 in the Higher one. Such low specific electricity use growth in the Lower demand projection could only be achieved by assuming that households would be soon saturated with presently known appliances, that few new types of appliances would be used in the future, and that the presently known ones would undergo vigorous efficiency improvements.

Water heating needs are not projected to change much over the current levels. Cooking energy requirements and cooking practices are assumed to undergo rather homogeneous efficiency improvements throughout Europe, resulting in energy requirements lower by 30 to 70 percent than today.

In the service sector similar considerations as in households determine the long-term energy needs. Here, however, instead of the number of persons living in a dwelling, the total labor force in the service sector would be instrumental for the level of energy use in the future. This labor force determines the required working area. Table 5.15 gives the expected energy requirements per square meter per year. However, it is assumed that air conditioning will be used more intensively. At most 10 percent (South Europe) of households are assumed to be air-conditioned in 2100, while in the service sector up to 70 percent of working area is assumed to be air-conditioned. The specific space heating requirements are projected to improve by up to 60 percent in the Lower, and by about 30 percent in the Higher demand projection.

Tables 16A and B summarize the useful and final energy requirements in the households and services.

Table 5.15. Projected Useful Energy Requirements for the Service Sector

	1975				2100, Projection							
					Higher Demand				Lower Demand			
		kWh/m² per year				kWh/m² per year				kWh/m² per year		
Western Europe	Work. Area ($10^6 m^2$)	S+W Heat.	Air Cond.	El. Appl.	Work. Area ($10^6 m^2$)	S+W Heat.	Air Cond.	El. Appl.	Work. Area ($10^6 m^2$)	S+W Heat.	Air Cond.	El. Appl.
North Europe	230	279	4	80	380	198	25	90	380	116	11	60
Central Europe	1200	256	8	80	240	209	41	90	2400	128	41	75
South Europe	1030	174	9	40	3350	139	65	80	3350	70	37	40

Work. Area ... Working Area
S+W Heat. ... Space and Water Heating
Air Cond. ... Air Conditioning
El. Appl. ... Electrical Appliances

Table 5.16A. Energy Requirements in Households and Services, Higher Demand Projection (GWyr/yr)

Use	Base Year	Projection			
	1975	2000	2030	2060	2100
Useful Energy					
Space Heating	203.1	204.5	236.3	266.7	307.3
Water Heating	48.0	71.9	104.9	119.0	138.0
Final Energy					
Electricity	38.4	97.3	150.6	201.7	270.0

Table 5.16B. Energy Requirements in Households and Services, Lower Demand Projection

Use	Base Year	Projection			
	1975	2000	2030	2060	2100
Useful Energy					
Space Heating	203.1	163.0	144.4	131.8	114.6
Water Heating	48.0	61.8	83.5	88.2	94.9
Final Energy					
Electricity	38.4	84.4	97.8	108.3	128.5

Energy Demand and the Scenarios

The previous sections have outlined our approach of evaluating energy demand and the salient assumptions made about the demand components that determine the future energy requirements in each sector of the economy. Two sets of energy demand components were evaluated on the basis of the same GDP and population growth. Thus we have implied a bifurcation of the future trends, reflected in the Higher and the Lower energy demand projections. In many ways these two demand projections are mutually exclusive since the underlying assumptions imply drastic changes when compared with current life-styles and the structure of the economic and social systems. We do expect that there would be a rich menu of possible demand levels between the two projections as they do represent extremes. If the society should choose to go in one of the outlined directions, then it would soon be difficult to reverse the social decision and choose the other extreme path in the future.

This last observation cannot be validated in a formal manner, but it is not foreseeable that such drastic structural and life-style changes implied by the Lower demand projection could be "reversed" somewhere along the path into the 21st century to result in the Higher demand projection and vice-versa. The bifurcation of the two projections is too large beyond the next 30 to 50 years so that the transition "window" cannot be extended indefinitely. This observation will become more obvious in Chapter 7 when we describe the structure of the energy supply systems that is drastically different from the current one. Today we consume by and large exhaustible energy sources and we envisage in the future energy systems based on sustainable energy sources, but the supply systems would be different for the two demand projections.

The two demand projections we have discussed so far result in two demand levels for energy services in the transportation sector, and useful and final energy in other sectors. The actual amount of energy that is required in these projections depends on how each of the demand categories is supplied. The simplest possibility of evaluating the demand in terms of final energy is to assume that also in the future the demand categories would be supplied in an analogous way as today. In other words, the evaluation would imply that no additional structural changes would take place beyond those that are reflected in the structure and the activity levels of each demand category. The salient assumption is therefore that the future final energy forms would be equivalent to the current ones, or that no structural changes would occur in the energy supply system.

Using this simplifying assumption, the two demand projections imply final energy demands of 3.16 TWyr/yr and 1.33 TWyr/yr by 2100. The corresponding average growth rates are 0.8 percent per year in the Higher demand projection and 0.1 in the Lower one. If we recall that the population and GDP growth levels were the same for both demand projections, the difference between the two demand levels is even more striking. The implied final energy-GDP elasticities are 0.5 in the Higher and 0.1 in the Lower demand projection. Tables 5.17 and 5.18 summarize these results. However, their usefulness is limited only to the direct comparisons with the base year, 1975, in order to highlight the nature of conservation and efficiency improvement measures assumed in the evaluation of the future energy demand categories.

The actual final energy requirements will depend on the structure of the energy supply system. The Lower demand projection corresponds to a decentralized supply system and the Higher one to a centralized supply system. The core of their common assumptions is the basis for the architecture of the overall scenarios. Thus the difference between these simplistically extrapolated final energy demand levels and the actual final demand levels in the scenarios illustrates the required changes in the energy supply system. These changes range from utilization of alternative sources of primary energy to new energy conversion and distribution systems, and they are necessary if the evaluated energy demand categories are to be fulfilled adequately, given their underlying assumptions. In fact, some reductions of total final energy supply due to structural changes occur in the Hard Solar scenario. The total final energy in the Soft Solar scenario is almost the same as the final energy calculated by extrapolating current energy supply to the year 2100 with the Lower demand

Table 5.17. Final Energy Demand Projection Based on the Current Energy Supply System, 1975 to 2100 (%)

Final Energy Supply	Base Year 1975	Projection Higher Demand 2030	Projection Higher Demand 2100	Projection Lower Demand 2030	Projection Lower Demand 2100
Europe					
North	8.9	6.5	5.7	7.4	7.4
Central	52.8	41.2	36.2	41.7	38.5
South	38.3	52.3	58.1	50.9	54.0
Use					
Thermal Low	42	33.5	26.4	33.2	22.0
Thermal High	14	12.7	11.9	12.7	9.1
(Thermal Total)	(56)	(46.2)	(38.3)	(45.9)	(31.1)
Coke	4	2.9	2.6	3.1	3.2
Feedstocks	7	10.5	16.4	10.2	16.2
Motor Fuels	21	23.2	22.5	22.1	24.4
Electricity	12	17.2	20.2	18.7	25.1
Total (TWyr/yr)	1.19	1.82	3.16	1.17	1.33

Table 5.18. Final Energy Demand Projection Based on the Current Energy Supply Structure and Final Energy Supply in the Hard and Soft Solar Scenarios, 1975 to 2100 (in TWyr/yr)

Final Energy Supply	Base Year 1975	Projection			
		Higher Demand		Lower Demand	
		2030	2100	2030	2100
Demand Projection	1.19	1.82	3.16	1.17	1.33
Per Capita Final Energy (kWyr/cap,yr)	2.96	3.49	5.76	2.25	2.46
Final Energy Elasticity (W/$75)	0.70	0.40	0.40	0.26	0.10
Hard Solar Scenario (Reduction in %)[a]	1.19	1.82 (0)	2.81 (12)		
Soft Solar Scenario (Reduction in %)[a]	1.19			1.17 (0)	1.39 (-4)

[a] Reduction of Final Energy in the Hard and increase in the Soft Solar scenarios is due to the structural change in the energy supply system. The changes include fuel substitution and higher energy conversion and transportation efficiencies (details will be explained in Chapter 8).

projection, but the supply structure is drastically different. Before we analyze the energy supply systems of these two scenarios we will first assess the energy resource available in Western Europe.

6. CONVENTIONAL ENERGY RESOURCES AND RENEWABLE POTENTIALS

Energy System Configuration and Resources

The supply of sufficient amounts of energy is one of the prerequisites for a stable and affluent future. This is an especially crucial issue for Western Europe, since it can be characterized as a region of the world with highly developed economies but with few endogenous energy resources. This has been clearly identified in the IIASA Global Study. Recalling some of the results described in Chapter 2, it is evident that the energy supply requires careful study, especially in Western Europe. Otherwise it would be by no means obvious how energy demand could lead to a reasonably consistent and adequate energy supply, conversion and distribution system via the complexity of market prices, international trade, government regulations and interventions, and physical and environmental constraints. This is more so the case in this study, since our objective is to investigate the possibility of a transition by the end of the next century to a sustainable energy system based on solar energy. The posed objective results in many conflicting constraints and opportunities for the integration of many components of energy demand and supply into a coherent energy system. Some of the important constraints are the endogenous resources and import opportunities in the short to medium term and the practical exhaustion of conventional resources in the long term. The opportunities are to use the energy and capital availability in such a way as to guarantee practically infinite supply of energy in the long term.

The consideration of such a transition to a sustainable energy system in the future requires a redefinition of the current view that the energy is supplied by a large number of more or less independent primary energy sources and energy conversion and distribution facilities. A sustainable energy system is an integrated system of a large number of *dependent* energy supply, conversion and distribution technologies. The whole energy system could be viewed as one complex process of interrelated components and functions in an analogous way as we would describe a single refinery. Thus in a sustainable solar energy system the solar thermal power plant, a biomass plantation and a roof-top solar collector are no longer independent sources of energy--they all have to be orchestrated, as if a central planning bureau would exsist, in order to provide the demanded space heat and final energy in the form of hydrogen, methanol and electricity. It is also obvious that such integrated systems are not only more complex than the current ones, but also that their design has to be carefully "planned" if the supplied energy is going to satisfy the projected demands. A simple example illustrates this important characteristic of sustainable energy systems. Consider a solar thermal power plant producing electricity and thermolytic hydrogen. Electricity is transported by long distance transmission links to consumption centers and hydrogen via a pipeline, but both are not consumed directly; instead, biomass is used with some of the thermolytic hydrogen to produce methanol which then supplies the required liquid fuels demand. All electricity is not consumed directly either because of the differences between the solar insolation profiles and demand loads. In part it is stored in pumped hydro facilities or converted into hydrogen by electrolysis before it is consumed. But the electrolytic hydrogen could be used again for liquid fuel production or electricity generation in fuel cells or it could be consumed directly as a gaseous fuel. This example shows that adequate back-up capacities could be provided both through excess facilities but also through careful systems design. Larger storage capacities (including the hydrogen pipeline) could eliminate the need for extra power plants and allow for the higher capacity utilization. At the same time, the supply system must be flexible enough to be adapted to new fuel mixes and fuel substitutions even during the life-times of the installed facilities. All of this could be achieved only if energy supply, conversion and distribution is viewed as a single but very complex dynamic system.

In the next chapter we will discuss two principally different energy systems that are based on sustainable sources of energy but that supply different demand patterns identified in the previous chapter. The transition from the current consumptive use of resources to these two sustainable energy systems and the corresponding energy demands are embodied in the Hard and Soft Solar scenarios. But before we present the two solar scenarios we will first outline the major constraints delimiting the future energy systems, perhaps the most important among them being the question of resources.

Assessment of Western European Energy Resources

It is a truism to say that because we live in a limited environment also the resources that are at our disposal must be finite. This statement must be clarified within the context of sustainable energy futures. By a sustainable energy system we do not imply that we intend to rely on unlimited resources, although such resources might exist at another level of conceptualization than chosen for the Solar Study. We mean that such energy systems use the available resources at sustainable levels, or in other words, the limited resources are invested in an energy system during the transition period in such a way that eventually sustainable levels of renewable resources could be exploited. For these purposes we distinguish the fossil resources, which cannot be used at sustainable levels, from other resources that are extracted from natural energy flows or from man-made flows and can be used at sustainable levels. An example of natural energy flows is the energy dissipated in run-off rivers that can be captured in hydropower plants or the part of the solar flux that could be used for energy generation in solar thermal power plants. An example of man-made energy flows is the cultivation of biomass in such a way that the energy harvesting does not exceed the sustainable levels of the "biomass stock". A somewhat analogous example is the use of abundantly available depleted natural uranium in a breeder reactor with limited amounts of fissile material as a "catalyst" for energy generation. In all of these examples energy generation is achieved by relying on a flow and not a "stockpile" of resources, thus we speak of renewable energy resources. Within the context of the Solar Study we have considered six broad classes of resources: fossil resources which are truly limited, natural uranium resources which could be both limited or "renewable" depending on the energy conversion technology used, and four classes of truly renewable resources--biomass, solar thermal conversion, renewable electric conversion and on-site (user-oriented) renewable resources.

Fossil and Natural Uranium Resources

Fossil energy sources are limited and principally cannot be used in a sustainable manner (given a sufficiently long time horizon). Strictly speaking, they are not exhaustible because usually more resources could be discovered or would become exploitable given a higher price, but in practice this means that their availability is limited.

Today fossil resources supply almost 90 percent of consumed energy in Western Europe (see Table 3.3B), so that one of the objectives in both solar scenarios is to substitute these resources before they become too expensive and too hard to exploit by other renewable ones.

As was mentioned above, the natural uranium could be viewed as either a sustainable or exhaustible energy source depending on how it is used. The resource becomes sustainable if breeder reactors are employed; it is limited if burner reactors are used in the same sense as crude oil when it is burned to generate electricity.

Table 6.1 gives the estimates of ultimately recoverable, proved and additional, fossil and uranium resources for Western Europe (and Table 6.2. their average costs). The purpose of this table is not to quote the actual amounts that could or might be found underground but to give the orders of magnitude. The table shows that the resources are unevenly distributed within Western Europe and that the total amounts, except for coal resources in Central Europe, are not very large.

At current consumption rates (1975, see Table 3.3A) and assuming complete reliance on domestic resources, coal would last over 1000 years, crude oil about 20, natural gas about 45 and uranium about 230 years. This observation implies the obvious: either a shift to heavier use of coal and nuclear energy, a stronger reliance on imported energy, or an attempt to restructure the energy system and complete the transition to alternative energy sources in the future. The feasibility of the last possibility depends to a large extent on the magnitude of renewable energy potentials.

Table 6.1. Ultimately Recoverable (Proved and Additional) Resources (TWyr)

	Resource							
	Coal		Crude Oil		Natural Gas		Uranium[a]	
Europe	Proved Res.	Add. Res.	Proved Res.	Add. Res.	Proved Res.	Add. Res.	Proved Res.	Add. Res.
North	0.1	0.2	0.9	1.5	0.6	0.8	5.2	0.3
Central	76.4	275.3	2.8	9.2	3.6	3.3	0.1	0.2
South	12.1	6.8	0.3	1.1	0.7	0.2	1.4	1.3
Western	88.6	282.3	4.0	11.8	4.9	4.3	6.7	1.8

Proved Res. ... Proved Resources
Add. Res. ... Additional Resources

[a] Primary energy potential is calculated on the basis of once-through LWR fuel cycle. With breeders or more efficient burner reactors this potential is significantly higher (more than two orders of magnitude, about 1300 TWyr). The potentials are based on 431 x 10^3 tons proved and 113.8 x 10^3 tons additional natural uranium resources.

SOURCE: WEC (1980) and OECD NEA/IAEA (1977).

Table 6.2. Costs of Ultimately Recoverable Resources (1975 constant dollars)

Energy Source	Recoverable Resource (TWyr)	Average Cost[a] ($/kWyr)
Coal	370.9	58.5
Crude Oil	15.8	90.0
Natural Gas	9.2	90.0
Uranium	8.5	4.2[b]

[a] Average costs include all mining and extraction, preparation and transport costs.

[b] Natural uranium costs are based on LWR use and its fuel cycle and not on advanced reactor type. With FBR the costs would be significantly lower due to more efficient use, but also the resource would become very large (about 1300 TWyr).

Biomass Potential

Under biomass energy potential we understand the photosynthetic fixation of solar energy in plants that can be harvested or collected and converted into a source of energy. Within this category the sustainable biomass potential is the exploitation of all renewable biomass ("flows") short of endangering the continuous regeneration of the biomass "stock". The main sources are the energy plantations and various agricultural energy by-products and wastes.

The potential depends on the yields achievable per unit area under cultivation and the area that could be devoted to energy generation without conflicts with other non-energy uses, such as food production, settlement patterns, recreation, etc. Table 6.3 gives the maximal yields (under laboratory conditions) for the most important sources of biomass energy in Western Europe. Table 6.4 shows how much of the low-conflict land could be used for various forms of "energy farming" in the three Western European areas. Given the land quality and climatic conditions and taking the maximal yields we estimate the total biomass potential of energy farms at 0.36 TWyr/yr on a sustainable basis. The implied energy density based on the actual area used for biomass production is quite high at about 0.70 W/m^2, but the energy "density" on the basis of the total area of Western Europe is

Table 6.3. Maximal Energy Yields from Biomass under Laboratory Conditions[a]

Biomass Source	Energy Yield (W/m^2)	Conversion Efficiency of Solar Insulation (%)
Forest waste	0.08	0.07
Timber	0.18	0.16
Whole tree	0.26	0.23
Harvest waste	0.30	0.27
Reeds	1.10	1.00
Sugar beat	2.31	2.10

a) Energy Yields were determined at 110 W/m^2 Solar Mean Radiation, which roughly corresponds to North Europe (see Table 3.2). At much higher solar radiation levels of say 200 W/m^2 (about maximal value for South Europe) yields of up to 3.5 W/m^2 could be achieved with Eucalyptus plantations.

SOURCE: Johansson and Steen (1978).

Table 6.4. Land Potential for Biomass (1000 km^2)

	Europe North	Central	South	Western
Marginal farm land	1.4	3.5	8.9	13.8
Energy forests	69.0	15.4	64.0	148.4
Catch crops	21.0	61.0	140.0	222.0
Pastures	14.0	34.0	72.0	120.0
Total area[a]	105.4	113.9	284.9	504.2
Energy GWyr/yr	114.9	80.8	159.3	355.0
Density W/m^2	1.09	0.71	0.56	0.70

a) Implicit shares of the land area are 9.1 percent in North Europe, 14.9 in Central and 10.9 in South Europe.

only about 0.08 W/m^2, whereas the current density of energy consumption is 0.33 W/m^2 (see Table 3.2). This rough calculation shows that the biomass resource alone is not sufficient to support a sustainable energy system even if exploited on a grand scale.

The biomass potential has been estimated on the basis of all resources up to the cost of 160 $(1975)/kWyr given in Table 6.5. Adding to this estimate the total waste potential of 0.18 TWyr/yr, given in Table 6.6 by source, we arrive at a renewable potential of all biomass sources of 0.54 TWyr/yr. This potential is shown by source in Table 6.7 and for the three parts of Western Europe in Table 6.8.

Solar Thermal Conversion Potential

The direct solar insolation potential is tapped by power plants that convert solar radiation into thermal energy that is either used for generation of electricity or other energy carriers such as hydrogen. Given the expected technical characteristics of these centralized conversion plants (see Chapter 7), the solar radiation and land availability are the major determinants of the resource magnitude. Based primarily on the criteria for identification of the available land, developed in the study of the solar thermal potential for the South West of the United States (Aerospace Corporation, 1974) and tailored to national conditions in Western Europe, conflicting land uses (for agricultural and other purposes) are specified and excluded from the consideration on a country-by-country basis. In addition, also land areas with slopes greater than 15° are excluded (greater than 25° for southerly sloping land). Finally, the seismic and

Table 6.5. Biomass Resource Cost Categories (1975 constant dollars)

Cost Category	Annual Resource (GWyr/yr)	Average Cost ($/kWyr)	Marginal Cost ($/kWyr)
Cheap	191	60	100
Moderate	349	120	160

Table 6.6. Waste Potential by Source (GWyr/yr)[a]

	Agri-cultural Wastes	Forest Wastes	Municipal Solid Wastes	Human Manure	Animal Lifestock	Total
North	3.8	42.2	1.7	0.2	1.6	49.5
Central	9.6	20.3	16.4	1.6	2.6	50.5
South	25.6	34.0	14.8	2.0	8.6	85.0
Western	39.0	96.5	32.9	3.8	12.8	185.0

a) For both Cost Categories (Cheap and Moderate)

Table 6.7. Biomass Resources by Source and Cost Category (GWyr/yr)

	Cheap	Moderate	Total
Marginal farm land	5.2	32.4	37.6
Energy forests	46.5	98.6	145.1
Catch crops	21.1	27.1	48.2
Pastures	36.9	87.2	124.1
Wastes	81.3	103.7	185.0
Total	191.0	349.0	540.0

Table 6.8. Biomass Potential per Cost Category and Region (GWyr/yr)

Europe	Cheap	Moderate	Total
North	60.5	103.9	164.4
Central	45.6	85.7	131.3
South	84.9	159.4	244.3
Western	191.0	349.0	540.0

strong wind activity zones and ground conditions (e.g. sand) have been considered as exclusion criteria.

The potential of low conflicting land in North Europe was not great due to already large land "allocation" to the biomass potential, and it was limited in Central Europe largely due to higher population densities (see Table 3.2) and extensive agricultural land use. Adding to this the relatively low mean solar radiation in North and Central Europe (around 120 degree-days against almost 200 in South Europe, see Table 3.2), high cloudiness and low direct beam inclinations, the solar thermal potential was indeed limited. As a consequence, we have only allocated the potentially available low-conflict land below 50° North latitude (dividing Western Europe through South France, North Italy and Yugoslavia) to solar thermal conversion. The low-conflict land areas above 50° North latitude we reserved for the photovoltaic conversion of solar insolation to electricity (discussed below). The area of Europe extending below 50° North is segmented into three insolation zones, as shown in Figure 6.1.

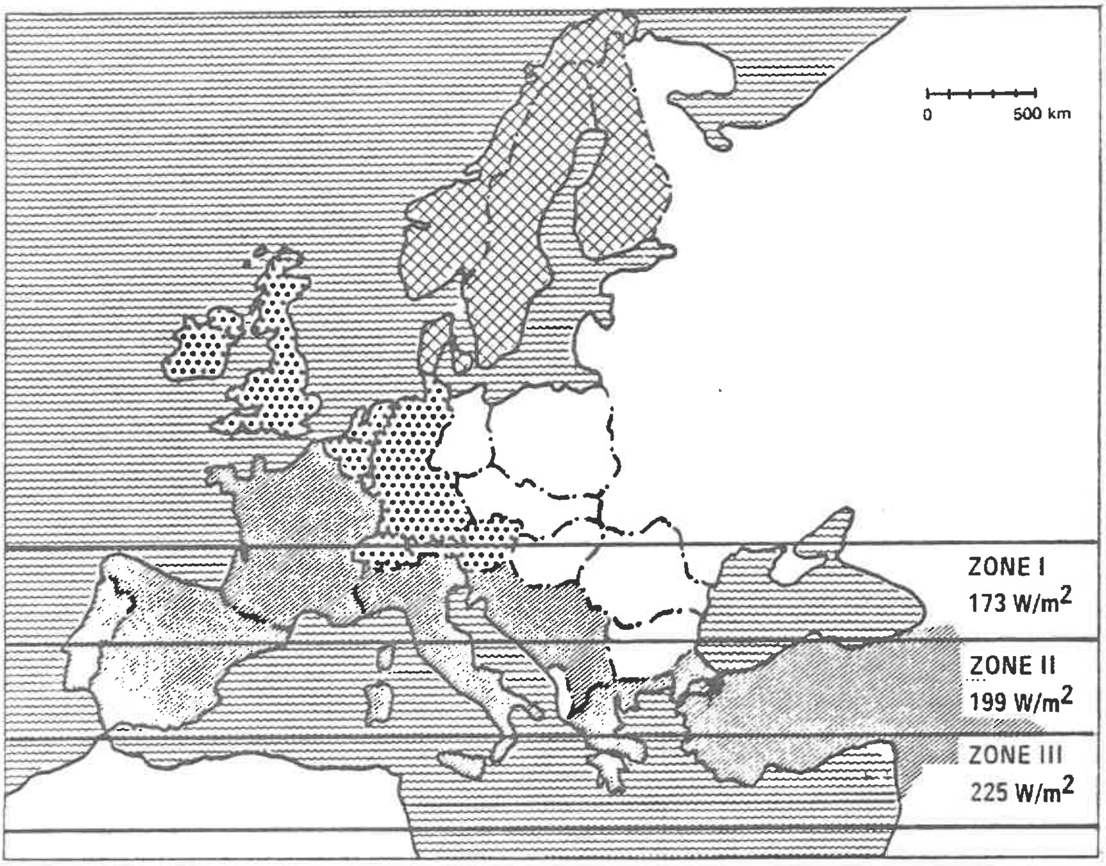

Figure 6.1. Three high solar insolation zones of Western Europe.

Due to the high uncertainty in the outlined procedure for the estimation of the actual low-conflict land availability we have identified in Table 6.9 the lower and upper bounds of this land potential for the three insolation zones. In terms of the total area of Western Europe this land potential represents between 0.4 and 2.3 percent of the land surface. Taking the upper bound as the maximal potential, the solar thermal conversion could contribute about 2.56 TWyr/yr of primary energy equivalent. Table 6.10 gives this potential and equivalent amounts of final energy depending on the type of solar thermal conversion plants used; namely, it is possible to generate electricity (with or without internal storage) or thermolytic hydrogen. The resulting renewable potential is large, it exceeds the current Western European primary energy consumption by 70 percent and is about five times larger than the biomass potential due to high generation densities of 43 W/m^2. However, it must be considered that this potential is unevenly distributed even within South Europe. More than 50 percent would originate from Zone III which extends over South Spain and Turkey.

Renewable Electric Potential

There are a number of renewable energy sources that are suited mainly for generation of electricity. In Western Europe these include hydropower, wind and wave power, but also photovoltaic conversion of solar radiation into electricity.

Table 6.11 gives the estimates of the maximal potentials of these renewable sources for Western Europe. Hydropower is the only source that is already under extensive use in Western Europe. Hydropower supplies 45.4 GW(e)yr/yr to the current electricity generation (1975, see Table 3.5). We estimate the European potential at more than twice the current use at about 108.9 GW(e)yr/yr (Partl, 1977). This potential includes the runoff river plants. It does not include the pumped hydrostorage plants, which are also foreseen in our scenarios for short-term (daily) storage of electricity which is necessary for bridging the gaps between electricity demand and generation profiles. The exploitation of this hydropower potential would require an all-out effort to install power plants. Table 6.11

Table 6.9. Land Potential for Solar Thermal Conversion[a]

Country	Land Area (1000 km^2)	Insolation Zones Area (1000 km^2)[b] I	II	III	Total	Share of Land Area (%)
France	544.0	(0.9- 3.5)			(0.9- 3.5)	(0.2-0.6)
Greece	131.9		(0.2- 0.9)	(0.2- 0.9)	(0.3- 1.7)	(0.2-1.3)
Italy	301.3	(0.1- 0.8)	(0.3- 1.6)	(0.1- 0.8)	(0.6- 3.1)	(0.2-1.6)
Portugal	92.1	(0.3- 1.7)			(0.3- 1.7)	(0.3-1.8)
Spain	504.8	(2.2- 6.5)	(2.4- 7.2)	(0.2- 0.7)	(4.8-14.4)	(1.0-2.9)
Turkey	780.6		(6.7- 6.5)	(2.0-26.0)	(3.7-32.6)	(0.5-4.2)
Yugoslavia	255.8	(0.3- 1.8)	(0.1- 0.6)		(0.4- 2.4)	(0.2-0.9)
Total (South Europe)	2610.5	(3.8-14.3)	(3.6-16.8)	(3.4-22.4)	(11.0-59.5)	(0.4-2.3)

[a] Numbers may not sum due to round-off errors.

[b] Values in parentheses: First value for lower and second for higher estimate.

Table 6.10. Solar Thermal Energy Potential by Insolation Zones

Europe	Potential Area[a] (1000 km^2)	Mean Solar Radiation (W/m^2)	Primary Energy Equivalent[b] (TWyr/yr)	Primary Energy Density (W/m^2)	Secondary Energy Equivalent		
					Electricity[c] (TW(e)yr/yr)	Electricity with Storage[c] (TW(e)yr/yr)	Hydrogen[d] (TW(th)yr/yr)
Zone I	14.3	173	0.52	36.36	0.19	0.14	0.25
Zone II	16.8	199	0.70	41.67	0.26	0.18	0.34
Zone III	28.4	225	1.34	47.18	0.50	0.35	0.64
Total	59.5	196	2.56	43.03	0.95	0.67	1.23

a) Higher estimate of the land potential.

b) Calculated on the basis of a 21% efficiency of conversion of solar radiation to heat.

c) Heat to electricity conversion efficiency of 37% was assumed (implying more than one-stage turbine). Electricity with storage includes a 12 hour thermal energy storage (before turbine-generator unit).

d) Thermolysis Hydrogen Generation Plant with 48% conversion efficiency.

Table 6.11. Renewable Electric Conversion Potentials: Hydro, Wind, Wave, Photovoltaics

Europe	Hydro		Wind		Wave		Photo-voltaics[b]		Total Potential		Primary Energy Equivalent[a]
	Total (GWyr/yr)	Local (%)	Total (GWyr/yr)	Local (%)	Total (GWyr/yr)	Local (%)	Total (GWyr/yr)	Local (%)	Total (GWyr/yr)	Local (%)	(TWyr/yr)
North	37.2	5.9	88.1	6.6	4.4	0.0	224.4	100.0	354.1	65.6	0.96
Central	25.5	13.7	199.1	6.6	7.4	0.0	27.1	100.0	259.1	16.9	0.70
South	46.2	9.0	181.0	6.6	8.1	0.0	466.3	100.0	701.6	68.8	1.89
Western	108.9	9.0	468.2	6.6	19.9	0.0	717.8	100.0	1314.8	57.7	3.55

a) Primary Energy Equivalent has been calculated assuming the implicit thermal to electricity conversion (as if fossil energy sources were used to generate the electricity) of 37%.

b) Local Photovoltaic installations do not include on-site (e.g. roof-top) collectors, this potential is given in Table 6.13. Land area requirements are 33.5 x 10^3 km^2 in North Europe, 4.6 x 10^3 km^2 in Central and 45.7 x 10^3 km^2 in South Europe (implied energy densities are 18.09, 5.89 and 27.55 W/m^2 for the three parts of Western Europe).

shows that about 9 percent of the potential is suitable only for local use, which means that also a very large number of smaller plants would be installed wherever possible.

There are a variety of water requirements that compete with the exploitation of this potential. Examples are the irrigation needs, especially in view of the biomass use for energy generation, river navigation, etc. In addition scenic and ecological constraints must be observed. In general, however, it could be expected that the economic considerations would be favorable to the exploitation of this potential, since the technology is well in hand. We should also note that the hydropower potential given in Table 6.11 is based only on the estimates of continental Europe and it does not include Greenland's glacier power which would almost double the European hydropower resource (with a potential of up to 90 GW(e)yr/yr, see Partl, 1977).

The estimate of the technical potential of wind depends on local meteorological conditions and the specifications of wind turbines suitable for tapping the resource. Very large machines could utilize higher altitude winds, but would interfere with each other if they are placed at close intervals downwind. Unfortunately, an exact estimate of the wind resource is problematic since the meteorological surveys record wind speeds at a standard height of ten meters above ground level. According to such measurements the highest wind speeds of up to 8 meters/second are attained off the west coast of Ireland, the United Kingdom and the Arctic (Dörner, 1974). The areas bordering the Atlantic Ocean, the North Sea and the Baltic Sea and parts of the Alps have mean wind speeds in excess of 6 meters/second while wind speeds range between 4 to 6 meters/second in larger areas including the Mediterranean coastline.

We have made two simplifying assumptions with respect to the wind machines suitable for direct electricity grid connection and the small wind turbines for local use (farms and rural areas). The representative large-scale wind plant has an annual electricity generation potential of about 580 kW(e)yr/yr per site and the small-scale units designed for local use have a generation potential of about 2 kW(e)yr/yr per unit, both at wind speeds of about 5 meters/second.

Given these assumptions, we base the technically feasible potential on the availability of land for the installation of plants in very windy areas with speeds exceeding 5 meters/second. This potential has been estimated on a country by country basis. It is based on potentials for the FRG (Jurksch, 1980), France (Goethals, 1980), Denmark (Sørensen, 1980) and Sweden (Johansson and Steen, 1978, Lönnroth et al., 1980) and extrapolations for Finland, Greece, Turkey and Yugoslavia using Sørensen's method. These potentials confirm the assessment given in ASA (1975). Table 6.11 gives the resulting potential of 468.2 GW(e)yr/yr which is a very large resource--40 percent would be enough to supply the current electricity consumption of Western Europe (1975, see Table 3.5). About 6.6 percent of this potential would consist of the small local wind turbines, which correspond to the current level of fuel oil use in power plants. In fact, the wind potential could be even expanded significantly using the offshore sources and higher level over-land wind machines (200 meters and higher above ground level). Such considerations would enlarge the resource, but at the same time we have already made some optimistic assumptions, that not fulfilled would lower the estimate. Specifically we have assumed that wind machines could be emplaced whenever the average wind speeds are favorable (above 5 meters/second) and wherever the low-conflict land is available, ignoring the construction difficulties in some regions and that in some very windy areas the power plants would be particularly vulnerable to destructive storms.

The contribution of wave energy is very small compared with wind and even hydropower. Table 6.11 gives the wave potential of Western Europe at 19.9 GW(e)yr/yr. This is a low figure considering that there are many schemes proposed for harvesting this energy source, particularly in the United Kingdom, where wave power is estimated as high as 8 to 9 GW. We have abstained from exceeding such favorable estimates due to technical difficulties of this resource. The main problem is that the machines must be able to convert energy with high efficiency from 3 meter waves while being able to withstand the onslaught of 30 meter waves. This observation pertains to all coasts where wave power has significant potential. No devices with this capability are yet in the offing.

The largest solar resource without intermediate thermal energy conversion steps is the direct solar electric conversion using arrays of photovoltaic cells. The resource, with an estimated potential of 0.72 TW(e)yr/yr, given in Table 6.11, is almost as large as the solar thermal potential (0.95 TW(e)yr/yr, see Table 6.10).

The photovoltaic cells are inherently modular and responsive to both diffuse and direct radiation. These two features have favorable implications that can hardly be overestimated. First, in middle latitudes of Western Europe it is not impossible to devote even relatively large amounts of land (on the order of thousands of km^2) to solar power uses, but not in large units. Second, the possibility of using diffuse as well as direct solar radiation makes photovoltaic applications viable even in areas where the cloudiness is rather high. In actual cases, given the prevailing land use and climatic conditions in Central and North Europe, these two features of photovoltaic solar conversion make a great difference when compared with solar thermal conversion plants. This was actually the reason for limiting the solar thermal conversion potential to latitudes below 50° North and reserving the more cloudy areas of the North and densely populated areas of Central Europe for photovoltaic conversion. Finally, photovoltaics have no moving parts, have potential life times that substantially exceed those of thermal conversion power plants, and exhibit efficiencies of up to 20 percent. This feature, in conjunction with modularity and sensitivity to diffuse radiation, makes the photovoltaic systems especially suited for local uses. In addition, for exactly the same reasons, the on-site potential (e.g. on the roof-top) of photovoltaics is also significant and will be discussed below together with other on-site renewable energy sources.

Unfortunately, there are no ideal energy alternatives and the crucial problem with photovoltaic cells are the economics of the high capital costs. These costs, however, are expected to decrease substantially, especially considering our long time horizon of over 100 years. We will return to the question of cost of all resources when we describe the configuration of the whole energy system for the two solar scenarios.

On-Site Renewable Energy Potential

We have assumed that the user-oriented renewable energy sources are limited to the areas in the immediate vicinity of the user. These areas are given in Table 6.12 and include roof and south wall areas of residential and commercial buildings and roof and immediate ground area of industrial facilities. They are suited for installation of water heating systems and photovoltaic arrays. The potentials for energy generation are given in Table 6.13 and represent an optimal allocation of the available area to useful heat and electricity generation. The numbers identify the portion of the actual roof area that can be applied for active solar heating. For example, the roof of a given house is assumed to contain solar warm water systems for that house and does not include the excess capacity to heat other houses that may not have the adequate roof area. The photovoltaic arrays are assumed to be installed over the total roof area not used for active heating and over southern wall areas. The potentials are significant; the photovoltaic electricity and useful heat potentials are almost equal to that of hydropower (see Table 6.11) in terms of electricity alone in each sector (households/services and manufacturing). The implied energy generation densities of on-site renewable resources are about 9.74 W/m^2 compared with 0.70 W/m^2 for biomass and 43.03 W/m^2 for solar thermal conversion. This is a clear indication that although they represent a large resource, their use must be limited to the vicinity of the user, otherwise, on a large-scale operation, the devices would be too cumbersome.

Table 6.14 summarizes all of the domestic Western European energy potentials in terms of the equivalent primary energy (although the conversions cannot be precise) in order to compare the orders of magnitude. The renewable energy sources have been expressed in terms of their cumulative potential contribution over a period of 100 years. All numbers represent maximal potentials.

These resource potentials show that the lack of resources alone could not be considered as a constraint in itself over the next 100 years or more, even if the current primary energy consumption (see Table 3.3) should increase seven-fold. Thus,

Table 6.12. Area Requirements for On-Site Thermal and Photovoltaic Energy Potentials (1000 km^2)

	On-Site Thermal					On-Site Photo-voltaics	
	Households/Services		Manufacturing				
Europe	Roof	South Wall	Roof	Ground Area	Total Area	Total Area	Share of Land Area (%)
North	0.3	0.1	0.3	0.8	1.5	33.5	3.0
Central	2.6	0.5	1.2	2.8	7.1	4.6	1.3
South	4.8	1.6	2.0	4.8	13.2	45.7	2.3
Western	7.7	2.2	3.5	8.4	21.8	83.8	2.3

Table 6.13. On-Site Renewable Energy Potentials[a] (GWyr/yr)

	Households/Services		Manufacturing		
Europe	Photovoltaics[b]	Useful Heat[c]	Photovoltaics[b]	Useful Heat[c]	Total Primary Energy Equivalent[d]
North	2.3	10.1	6.7	8.0	54.7
Central	15.2	64.0	13.6	43.3	248.8
South	78.5	100.3	65.0	89.8	724.7
Western	96.0	174.4	85.3	141.1	1028.2

a) On-site potentials include the roof and south-wall areas of houses and also the ground surrounding the manufacturing facilities.

b) Final electricity from photovoltaic on-site pannels.

c) Useful high and/or low temperature heat.

d) Primary energy equivalent was derived assuming thermal to electricity conversion efficiency of 37% and additional electricity transportation and distribution savings of 15%, and assuming the crude oil equivalent of the useful high to medium temperature heat at about 64% (in households/services) and 73% (in manufacturing) conversion efficiency.

Table 6.14. Ultimately Recoverable Resources and Renewable Potentials[a] (TWyr)

		Recoverable				Renewable[b]			
Europe	Total	Coal	Crude Oil	Natural Gas	Uranium[c]	Biomass	Solar Thermal[d]	Renewable Electric	On-Site
North	129	0	2	1	5	16	0	98	5
Central	481	352	12	7	0	13	0	71	25
South	568	19	1	1	3	24	256	192	72
Western	1178	371	16	9	9	54	256	361	102

a) All numbers represent maximal potentials, e.g. for fossil energy proved and additional resources are included and for renewable also the most expensive categories. The numbers may not always sum due to round-off errors. Zeros represent insignificant potentials at the terawatt level and not the complete lack of resources.

b) Renewable potentials have been calculated assuming their availability over a time period of 100 years (from 2000 to 2100), hydropower over 120 years. Thus their annual potentials can be obtained by dividing through 100.

c) Natural uranium could also be considered as a "renewable" resource if used in breeder reactors.

d) Solar thermal potentials in North and Central Europe are not zero, but they were not included due to high costs--it is cheaper to use the potential in South Europe and transport the energy to consumption centers of North and Central Europe.

considerung the potentail availability of resources, the projected Higher and Lower energy demands from the previous chapter appear to be modest. Unfortunatley we are facing a number of overlapping problems. The availability of energy potentials and their actual technical and economic utilization are two different issues. The conventional (fossil) resources are obviously not sufficient and the utilization of renewable energy resources requires the development of new technologies, and their commercial use on a grand scale. The potentials are a collective asset of whole Western Europe, they are very unevenly distributed among and even within the individual countries. Thus their exploitation requires a cooperative effort and a long time horizon. The fossil energy sources will become more expensive, dirtier and more difficult to extract and convert to useful energy forms, and at the same time an enormous effort is required for a continual transition to sustainable energy sources. This all points to the fact that the architecture of the energy supply system is a crucial issue that will be instrumental for the feasibility of a transition to a sustainable energy future.

Constraints

Before we turn to the actual design of the energy supply systems of the two solar scenarios, we will consider the constraints that limit the implementation of every given energy system. These constraints must be viewed from a "macro" level as an aggregated sum of many different limitations. Some of them we can identify explicitly as for example land use, but others can only be interpreted as combinations of institutional, technical, economic, etc. factors.

To summarize land use requirements that we have identified above for each renewable source that requires significant areas for energy generation (i.e. has relatively low energy densities) Figure 6.2 compares the land requirements to sustain various electricity generating systems, each producing about 0.7 GW(e)yr/yr (6.1 TWh) of electricity. Table 6.15 identifies the important assumptions made in characterizing these electricity generating systems. Thus, from the standpoint of land-use requirements, the solar thermal energy conversion has the

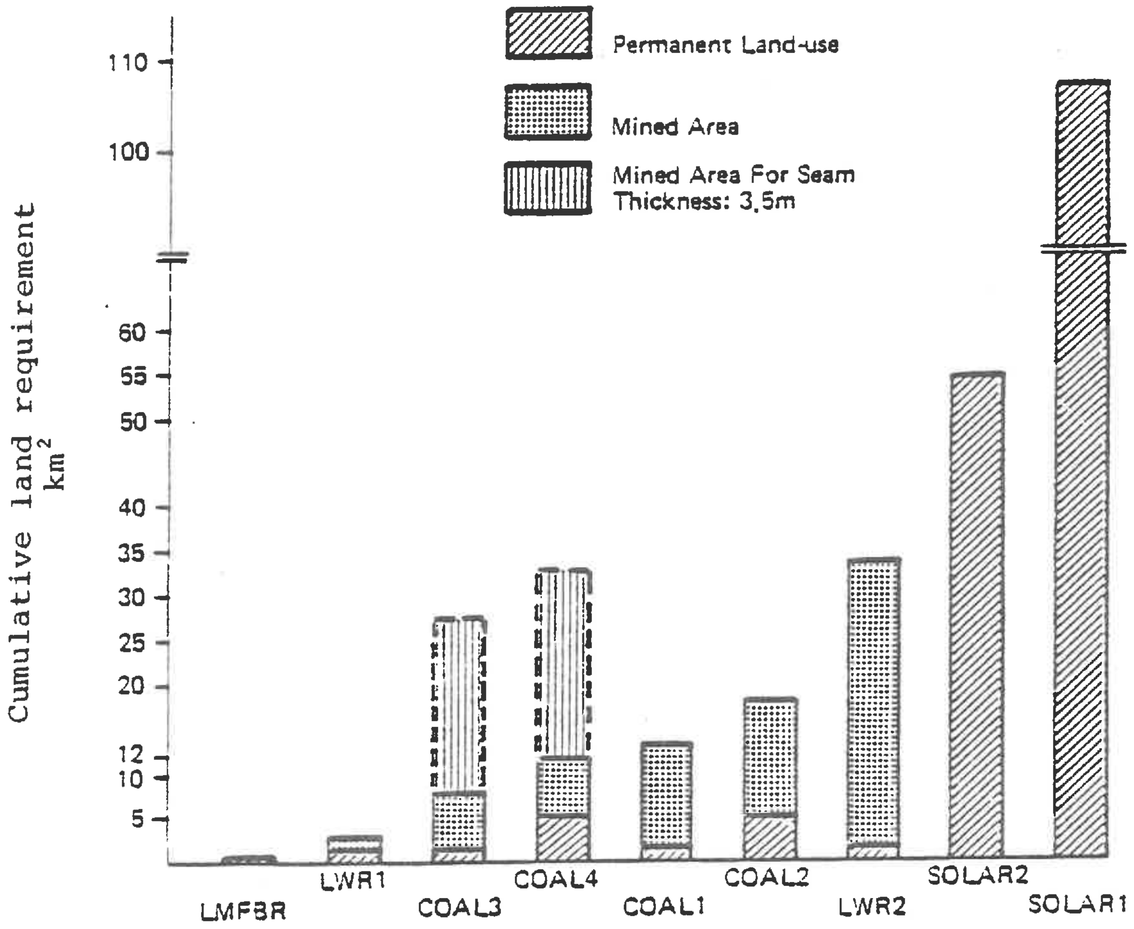

Figure 6.2. Cumulative land requirements (km^2) for energy chains producing 6.1 TWh electricity. The importance of the seam thickness of opencast mining is indicated as an example for Coal 3 and 4. For explanation see Table 6.15.

Table 6.15. Characteristics of the Electricity Generating Chains (6.1 TWh, 30-year life span)

	Coal 1	Coal 2	Coal 3	Coal 4	LWR 1	LWR 2	LMFBR	Solar 1	Solar 2
Mining	U.S. western underground coal mine, seam thickness: 1.5 m		U.S. western surface coal mine, seam thickness: 9.2 m		60% surface, 40% underground, 0.203% U_3O_8	Underground shale mine,	Chattanooga 0.007% U_3O_8	-	-
Preparation	Coal preparation plant				Uranium mill, enrichment, fuel fabrication		Uranium mill, fuel fabrication	-	-
Transport	Rail, 900 km	Slurry pipeline, 900 km	Rail, 900 km	Slurry pipeline, 900 km	Negligible	Negligible	Negligible	-	-
Power plant	1,000 MW(e), load factor 70%, conventional	1,000 MW(e), load factor 70%, fluidized bed, environmentally controlled	1,000 MW(e), load factor 70%, conventional	1,000 MW(e), load factor 70%, fluidized bed, environmentally controlled	1,000 MW(e), load factor 70%, thermal efficiency: 33%, 3.2% ^{235}U fuel		1,000 MW(e), load factor 70%, thermal efficiency: 40%, UF_6 tails and natural Uranium fuel	28 × 100 MW(e), STEC, direct radiation, 1,500 hrs/yr, 1,500 kWh/m^2/yr	14 × 100 MW(e) STEC, direct radiation, 2,700 hrs/yr, 3,000 kWh/m^2/yr
Electricity storage	-	-	-	-	-	-	-	6 hours on site thermal	
Reprocessing	-	-	-	-	Uranium reprocessing		Uranium and plutonium reprocessing	-	-
Waste storage	Negligible	Negligible	Negligible	Negligible	Low level waste storage, temporary (maximum 100 years), high level waste storage			-	-

highest needs per unit of generated electricity. This explains to an extent the reason for the careful evaluation of solar energy potential in terms of the low-conflict land availability in Western Europe. What these land requirements imply for the whole energy supply system is illustrated in Table 6.16, where land requirements for various renewable energy technologies are given as percentages of the Western European total land area. A figure of orientation is the 16.6 percent of the total land area for exploiting the biomass, solar thermal, photovoltaic and on-site energy sources. This area is about 751 thousand km^2, or about the same as the area of whole Central Europe (see Table 3.2), a large area indeed. Whether such an enormous undertaking is actually feasible we cannot judge now. However, it is clear that using this whole potential would involve unprecedented efforts and long-term planning. It is certain that this borders on the extreme of what can be characterized as a real energy alternative for Western Europe.

Table 6.17 and Figure 6.3 give the materials and health hazards, in terms of man-days lost, for each of the electricity chains given in Table 6.15. Here again it is possible to doubt the feasibility of using solar energy sources to the extent we have specified in the estimates of the potentials, but it is important that the reader realizes what it means in terms of such requirements to architecture a sustainable energy system based on renewable energy sources. It is not an undertaking that could be realized by simply relying on market forces acting today: Due to the large orders of magnitude of both land and material requirements an active effort is required. It is also obvious that this cannot be done "overnight". Therefore we now turn to constraints that act on a "macro" level in limiting the introduction of new technologies, we call them market penetration constraints.

Every new technology must pass three distinct phases of development before it can successfully compete with older, established technologies: It must show scientific feasibility, pass the technical feasibility tests in a demonstration facility and finally prove to be commercially competitive. After these three development phases it can substitute old technologies if it

Table 6.16. Summary of Land Requirements of Renewable Energy Potentials

Europe	Land Area (1000 km^2)	Biomass (%)	Solar Thermal (%)	Renewable Electric (%)	On-Site (%)	Share of Land Area (%)
North	1153.7	9.1	0	2.0	3.0	15.0
Central	762.3	14.9	0	0.6	1.3	16.8
South	2610.5	10.9	2.3	1.8	2.3	17.3
Western	4526.5	11.1	1.3	1.9	2.3	16.6

Table 6.17. Material Requirements for Construction and Operation of Electricity Chains (10^3 tons)

	Metals for Construction	Other Materials for Construction	Non-Energy Materials Operation (Cumulative 30 Years)	Energy Materials Operation (Cumulative 30 Years)	Total
Coal 1	43	151	8,287	79,000	87,480
Coal 2	65	140	23,566	84,000	107,770
Coal 3	44	142	4,000$^+$	79,000	83,186
Coal 4	67	130	23,230	84,000	107,430
LWR 1	41.8-56.6	192.7	132	2,700	3,066-3,080
LWR 2	43.4-58.2	192.7$^+$	132	119,300	119,668-119,683
LMFBR	33	276.3	*a*	800	1,103
Solar 1	844.3-1,930.4	3,298-6,778	*a*	0	4,142-8,708
Solar 2	666.4-965.7	2,005-3,390	*a*	0	2,671-4,355

[a] Not available.

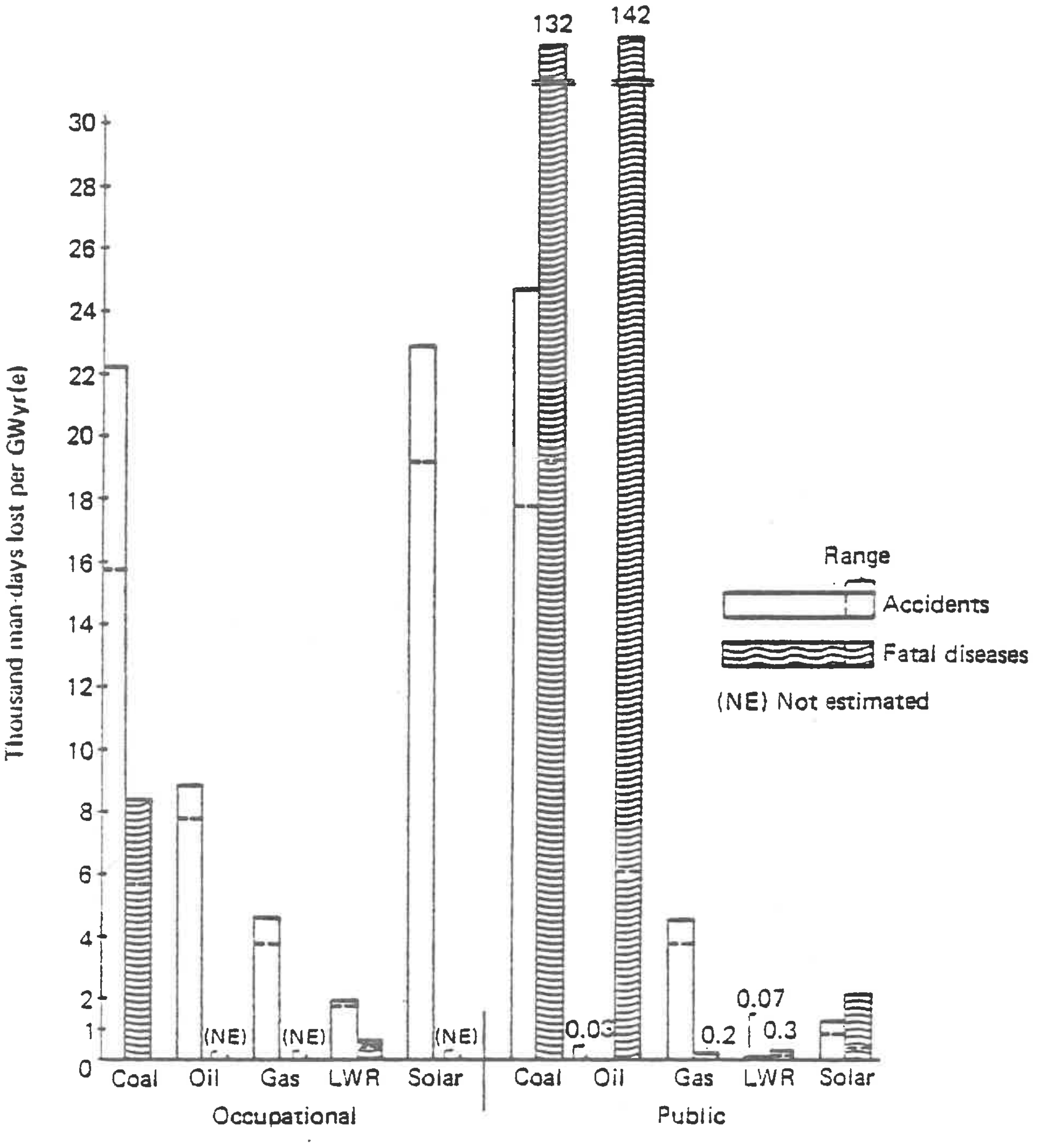

Figure 6.3. Man-days lost annually to supplying 1 GWyr(e) from each of five sources. Power plant life is 30 years.

becomes "acceptable". Figure 6.4 shows the historical substitution process of the major primary energy sources in Western Europe captured by the logistic substitution model (Marchetti and Nakicenovic, 1979). It appears that the substitution rates are rather regular (that they exhibit similar substitution "slopes"). In fact, it turns out that this is one of the major results of the market penetration analysis undertaken at IIASA: Substitution rates of competing technologies on one given market (in this case primary energy market) appear to be very regular and exhibit similar substitution rates. On the world level it took about 100 years for a given energy source to increase its market share from 1 to 50 percent of the market (see Figure 2.1), and in Western Europe only about 30 to 40 years. The typical build-up rates determined from historical data with the logistic substitution model are seen in Table 6.18. Assuming that these substitution rates, characteristic of Western Europe, would also prevail in the future, we can extrapolate that renewable energy sources cannot contribute more than 50 percent of primary energy supply after 2030 if not introduced before the year 2000. We observe this "constraint" explicitly in our scenarios by specifying the maximal build-up rates of new technologies. We will describe our assumptions in the next chapter.

In conclusion we may state that Western Europe has large renewable energy potentials at its disposal. Unfortunately these potentials can be exploited only under the condition that long time is allowed for their full introduction among other traditional energy sources and that very drastic structural changes take place in the whole economy and in particular in the energy system. In the previous chapter we outlined some of the important changes that could lead to the Higher and Lower energy demand projections for the next 120 years. Given the renewable energy potentials and possible constraints on their exploitation assessed in this chapter, we now turn to the structure of the energy systems in the two solar scenarios.

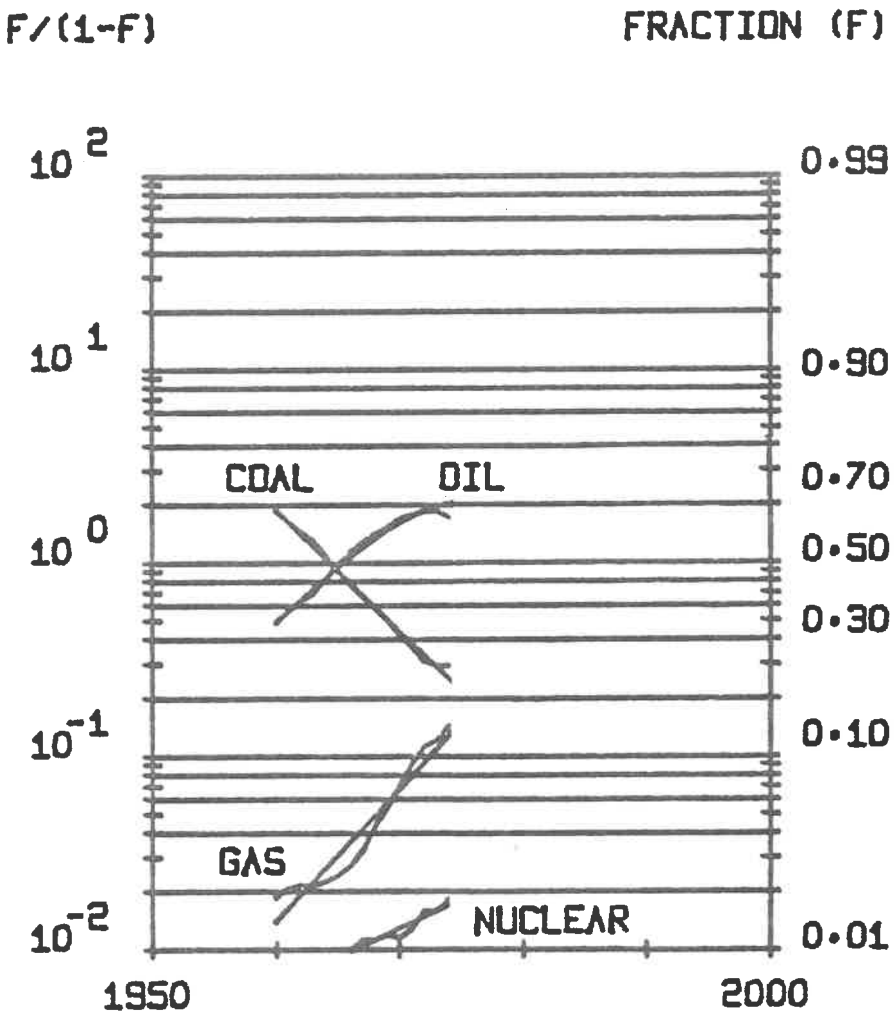

Figure 6.4. Primary energy substitution in Western Europe. Logarithmic plot of the transformation f/(1-f), where f is the fractional market share. Smooth lines are model estimates of historical data; scattered lines are historical data; straight lines show the logistic substitution paths.

Table 6.18. Historical Build-up Rates of Primary Energy Technologies

Region	Technology	Build-up Rate[a] (%/yr)	Introduction Date[b] (Year)
World	Oil	6.8	1880
	Natural Gas	6.8	1902
United States	Oil	7.7	1874
	Natural Gas	7.0	1879
Western Europe[c]	Oil	13.3	1930[d]
	Natural Gas	20.7	1958
	Nuclear	10.4	1967

a) Build-up rate is the exponential growth rate of the new technology (in absolute terms) as it grows from 1 to 10% of the market it serves.

b) Year when 1% market share was achieved.

c) Western Europe excluding Yugoslavia and Turkey (European OECD countries).

d) Introduction data for oil in Western Europe has been estimated.

SOURCE: Marchetti and Nakicenovic (1979).

7. ENERGY CONVERSION, TRANSPORTATION AND DISTRIBUTION SYSTEM

Energy Conversion and Use

Energy in its primary form can rarely be directly consumed. Exceptions are coal or fuel wood burned in a stove. In general energy must be extracted or collected, it must be converted into secondary energy forms, for example in a refinery or a power plant, and transported and distributed to the user before it can be put to use as gasoline in a car or electricity for lighting the house. This is a complex system comrising numerous separate technological processes. However, only a detailed analysis of this system can show whether and how a certain energy demand can be satisfied.

The following conceptualization of the general structure of the energy supply system will help to put this chapter in perspective (see Figure 7.1): It relies on the available resources of conventional energy sources and renewable energy potentials and after conversion delivers useful forms of energy to final use. The magnitude of recoverable resources and renewable potentials we have discussed in the previous chapter. The useful energy requirements were specified by the two energy demand projections in Chapter 5, along with the implied changes in the whole economy. In this chapter we will discuss how these two components, available energy and energy demand, are linked together by the energy supply system.

The energy system of Western Europe is modeled in MESSAGE II to include all energy conversion, transportation and distribution stages from primary energy sources to energy use. MESSAGE II is a linear programming model that optimizes the configuration of the whole energy system under the minimum cost criterion and constraints on build-up rates of technologies and on potentials that they could reach. We start with the current energy system of Western Europe and consider two possible evolutions up to the year 2100 as specified by the Hard and Soft Solar scenarios. Each of these two possible developments outlines the structural changes that are implied by the two scenarios. Both, however, lead to sustainable energy systems by the second half of the next century that are decoupled from further reliance on fossil energy sources.

In Chapter 4 we have outlined the basic characteristics of the proposed sustainable energy scenarios for Western Europe and have mentioned that each of them relies to the maximum possible extent on the specified "reference energy system". Before we describe these reference systems in detail, it is useful first to identify the various stages of energy conversion. Figure 7.1 illustrates the energy conversion steps and the resulting energy forms. Primary energy is the energy recovered from nature: water flowing over a dam, freshly mined coal or solar insolation over a given land area. Primary energy forms are the resources and potentials at our disposal we have discussed in the previous chapter. Primary energy is converted into secondary energy in several ways. Today central power plants produce electricity and sometimes district heat. Refineries convert petroleum to make convenient liquid fuels--gasoline, jet fuel, diesel and naphtha. When gasoline is not available, coal or biomass conversion plants could make liquid fuels. Natural gas is one of the rare forms of primary energy that can be used directly without conversion, but when it is not available central power plants could produce hydrogen either by electrolysis or thermolysis of water. Sometimes the conversion plant is at the end point of a system, as with nuclear fission energy or biomass, other times it is a simple machine, as with a hydroelectric or wind generator. But, regardless, there are conversion losses in going from primary to secondary energy and transmission losses in getting that energy to the consumer. It is wrong to think of these losses as wastes. They represent a trade-off of efficiencies: The use of energy to transform and transmit energy permits the end user to apply it efficiently for his purposes. These final steps are the conversion of secondary energy into final energy (e.g. liquid fuels and electricity) and of final energy into useful energy (e.g. space heat) which then produces energy services (e.g. person-kilometers traveled).

Each reference system covers the whole chain of energy conversion, transport and distribution from primary to final and useful energy forms. As a point of departure we will first describe the current "reference system" that is primarily based on the use of fossil fuels.

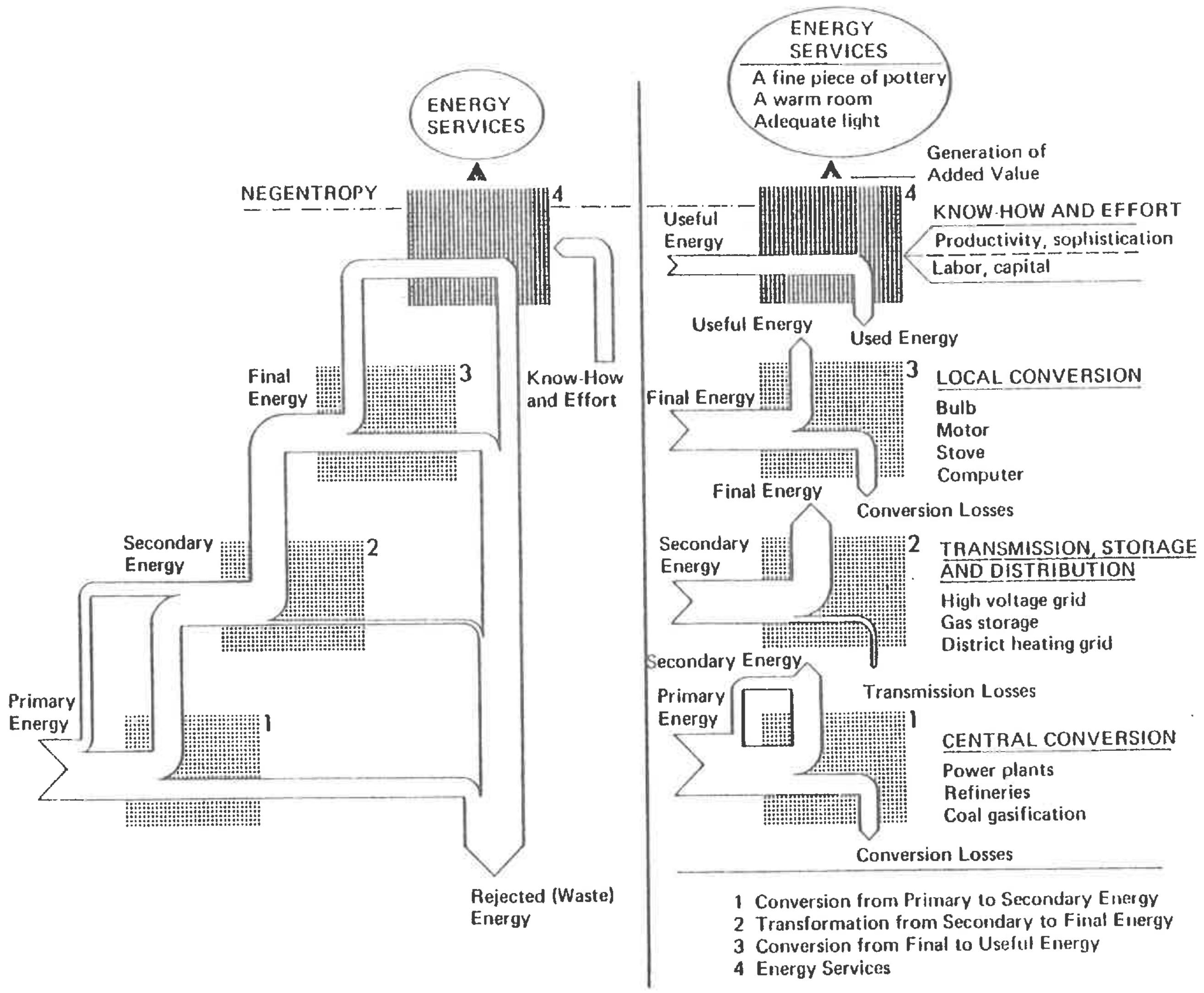

Figure 7.1. Energy conversion and uses.

Current Energy System

The current energy system of Western Europe is shown schematically in Figure 7.2. On the left are the primary energy sources that were described in the previous chapter and on the right the various final and useful energy demand components described in Chapter 5. As was described in Chapter 3 the main sources of energy today are coal, oil and natural gas. Nuclear energy and hydropower are used for electricity generation, and biomass use is limited to fuel wood burned for space heating purposes. Coal, oil and natural gas are used to produce both secondary energy fuels and electricity. Fuels, after conversion, are transported to final use by truck, rail or pipeline and electricity by grids. An important feature that emerges from Figure 7.2 is that the system is not very interdependent. The only connecting links at the central conversion stage are the electricity grids, otherwise each primary energy source is delivered to end use by its own transportation and distribution system. Within the system, there are no alternative liquid fuels that could replace crude oil refinery products. The fuel substitutability is largely limited to water and space heating and high to low temperature heat in industry. Thus the current energy system could be characterized by few interdependencies between conversion and distribution processes of various primary energy sources. In addition, most of the energy supply, except for hydropower and biomass use, is based on the consumptive use of fossil and uranium resources. Due to the limited amounts of endogenous resources that can be used in Western Europe today, the import dependence is also accordingly high (as was shown in Table 3.4) at about 53 percent of all primary energy consumed.

The reference energy systems of the Hard and Soft Solar scenarios represent a completely different mode of resource use. They are both based on sustainable use of renewable energy potentials. By the second half of the next century they are completely decoupled from consumptive uses of resources. In terms of the schematic representation of the energy system given in Figure 7.2, they can be viewed as a dual to the current energy system. By the time the transition is completed, fossil and nuclear energy is not used at all, instead only renewable

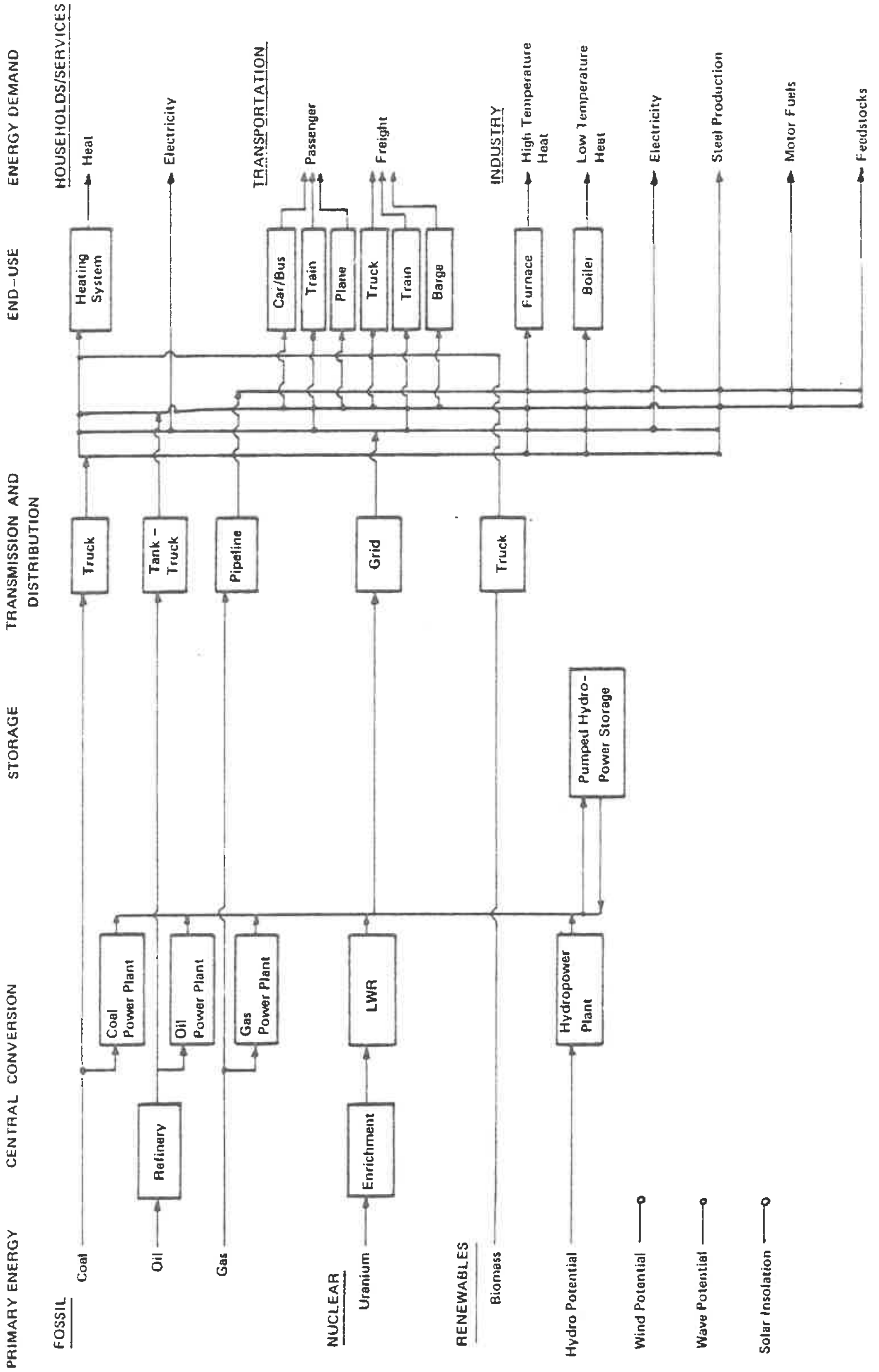

Figure 7.2. Current energy system.

energy potentials are relied upon while equivalent energy demand categories of the right hand side of Figure 7.2 are still satisfied through a more complex and interdependent energy conversion, transport and distribution process. They both imply a new energy system structure.

Between these extremes, the current energy supply and the two sustainable energy systems of the future, is the long transition period. During this transition the energy system includes elements from both present and future structures.

Hard Solar Energy System

The hard solar reference system relies on sustainable use of biomass, hydropower and solar thermal potentials. Hydropower is converted to electricity. Solar thermal insolation is converted into electricity in STEC plants located in South Europe. Two types of STEC plants are envisaged, without internal storage and with 12 hours thermal storage. The generated electricity is transported to other parts of Western Europe by long-distance DC transmission links. Some of the solar thermal plants produce hydrogen either by water thermolysis or on-site electrolysis. Hydrogen is transported to other parts of Western Europe by large pipelines that can also be used as a form of daily hydrogen storage through pressure variations (up to 10 percent of nominal pressure). Hydrogen can also be a source of electricity when burned in fuel cells. On the other hand, electricity can itself be used to produce electrolytic hydrogen after DC transmission and before distribution by the grid. Daily variations between electricity generation and demand are balanced by (underground) pumped hydro storage. Seasonal variations between delivered and demanded energy are balanced exclusively in the form of hydrogen as a secondary fuel and not by seasonal electricity storage. Biomass is converted to solid fuel by being compressed to reach energy densities similar to brown coal (about 1 kWyr per metric ton). It is however hardly used as a source of energy in this secondary form, instead it is either converted to methanol directly in an autothermal liquefaction process or after being blended with hydrogen. Thus altogether four forms of final energy are delivered in the hard solar reference system: biomass as a solid, methanol as a liquid, hydrogen as a gaseous fuel, and electricity.

Figure 7.3 reproduces the schematic diagram of the current Western European energy system together with the hard solar reference system and all interconnections between various conversion, transportation and distribution stages. The diagram, in its full extent, shows the transition phase of the energy system of the Hard Solar scenario. At the beginning (in the reference year 1975) only the current energy system is installed and slowly, as the scenario evolves, various components of the hard solar reference system are added. Toward the end of the next century, when the transition to the sustainable energy sources is completed, all of the components of the current system are eliminated. The complexity of the hard solar reference system and the transitional systems are apparent from the diagram in Figure 7.3. The interdependencies of various energy technologies are ever present at all conversion, transport and distribution stages. The whole energy system can be characterized as one large, complex process. Fuel substitutability is possible at almost all levels of the system, and the changing proportions between produced energy carriers are system induced. Even over periods of a single year the proportion between generated hydrogen and electricity changes. During the summer time, when solar insolation is abundant and energy requirements are relatively low, more hydrogen is produced and stored to be partially converted back to electricity during the winter months. This example illustrates the intricate interdependencies built into the supply system. Before we proceed to describe the characteristics of various energy technologies used in the energy system, we will first describe the reference system of the Soft Solar scenario.

Soft Solar Energy System

We have seen that a hard solar reference system represents a complete structural change when compared to the current energy system. However, it has one strong similarity to the current system: It relies almost exclusively on central energy conversion. In fact, the energy conversion is even more centralized

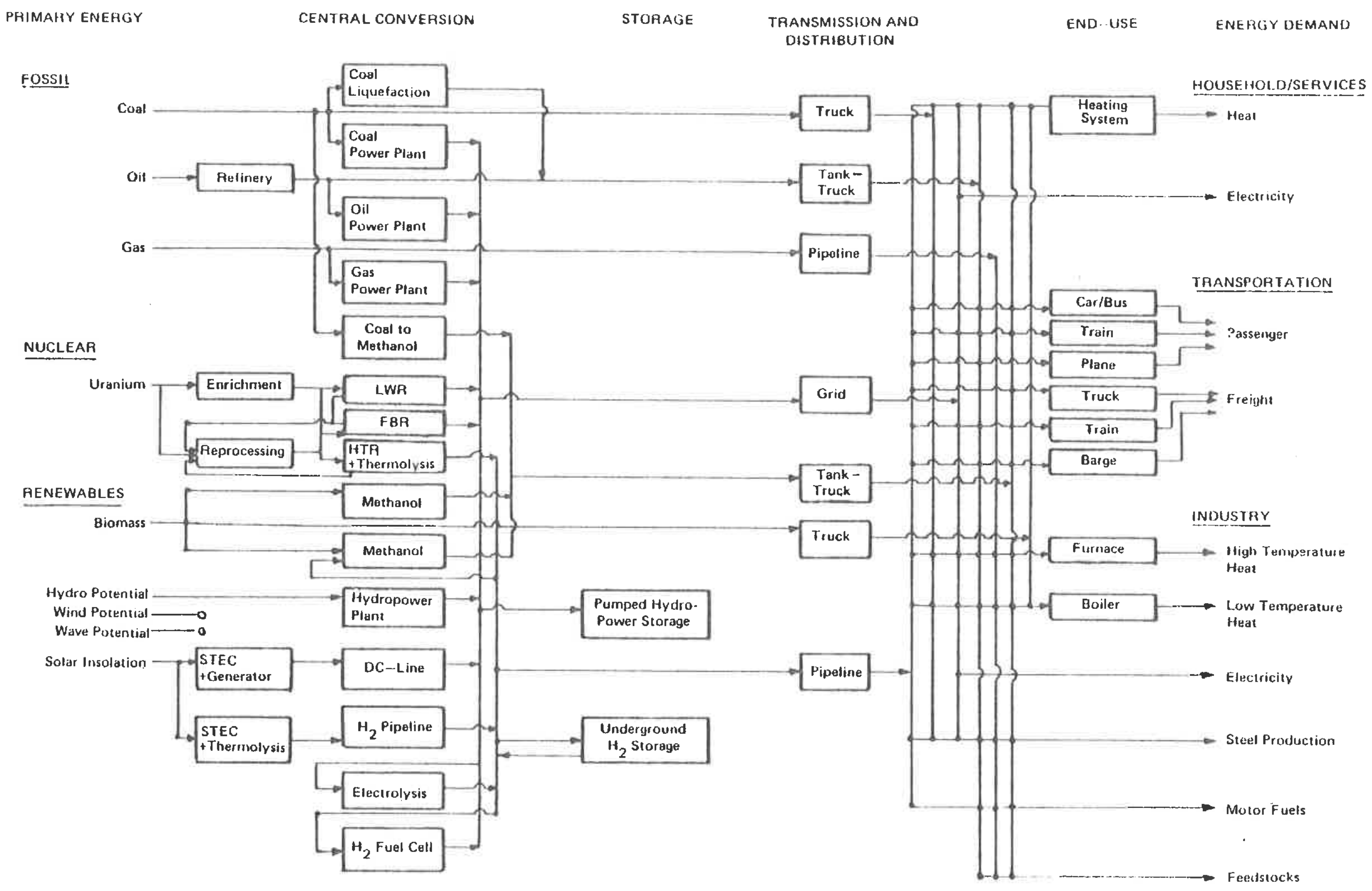

Figure 7.3. Energy system of the Hard Solar scenario.

than in the current system. In order to bridge the supply and demand the centralized solar thermal conversion in South Europe is connected with other parts of Western Europe by unprecedented long-distance energy transportation consisting of hydrogen pipeline and DC electricity transmission.

The soft solar reference system configuration relies to the maximum possible extent on decentralized, local, and on-site energy conversion. Thus, in the Soft Solar scenario the transition from the current system is both based on a complete structural change and increased user orientation in energy conversion itself. Today, user-oriented, on-site energy conversion is largely limited to some use of fuel wood for space heating and in few places small hydropower and passive solar space heating installations. This kind of on-site energy conversion is rather simple: Fuel wood is usually collected in the vicinity of the user and simply burned, on-site hydropower is only used if there is no electricity grid connection and is usually supplemented by a diesel back-up generator or battery storage. The soft solar reference system represents a different scale of operation, on-site conversion is used whenever possible going to extremely low energy densities per unit of conversion area. This means, for example, that all of the available roof area is used either for active solar heating or photovoltaic electricity. It also implies extensive use of the wind potential.

Table 7.1 illustrates the "level of centralization" of various conversion technologies foreseen in the soft solar reference system from user-oriented, on-site facilities to large-scale energy conversion of the hard solar reference system. The "level of centralization" (in this sense an inverse of the distance of energy conversion to the user) increases from the top of the table downward.

In the configuration of the soft solar reference system the highest preference is given to the on-site conversion. Only when the complete potential of such renewable energy is exhausted more centralized facilities are added in order to meet the energy demand. The preference is the lowest for the large-scale energy supply from solar thermal conversion in South Europe, represented by the hard solar reference system.

Table 7.1. Location of Energy Conversion Technologies with Respect to Final User, Soft Solar Scenario

Location	Technology	Energy Form
On-Site	Passive Solar	Heat
	Active Solar	Heat
	Small Photovoltaic	Electricity
	Solar Co-generation	Heat/Electricity
	Biomass Co-generation	Heat/Electricity
	Biomass Burner	Heat
Local	Large Photovoltaic	Electricity
	Small Windpower	Electricity
	Small Hydropower	Electricity
National	Large Windpower	Electricity
	Wave Power	Electricity
	Large Hydropower	Electricity
Continental	Solar-Electric	Electricity
	Solar-Thermal	Hydrogen

Figure 7.4 gives the schematic representation of the current system and the soft reference system. The primary energy inputs are similar to hard solar, except that now also on-site and local level renewable sources are used: wind, wave and photovoltaic energy potentials. The high degree of user orientation can be seen from more elaborate integration of end use energy potentials supplying useful and final energy to households, services and industry. These range from active solar space heating of residential and commercial buildings to on-site photovoltaic and solar thermal conversion in industry. Such systems need minimal energy transportation and distribution systems (energy is converted on site or in the immediate vicinity of the user) so that at first glance they would appear to reduce the complexity of the soft reference system. However, they all need back-up systems and in addition the potentials of on-site systems are insufficient to cover the demanded useful and final energy. Thus most of the supply system encountered in the Hard Solar scenario has to be added in order to achieve the adequate energy supply, but of course, on a smaller scale. This all adds to the complexity of the soft solar reference system. Furthermore, the interdependence of different conversion, transport and distribution stages and on-site conversion are more intricate than in the hard solar system.

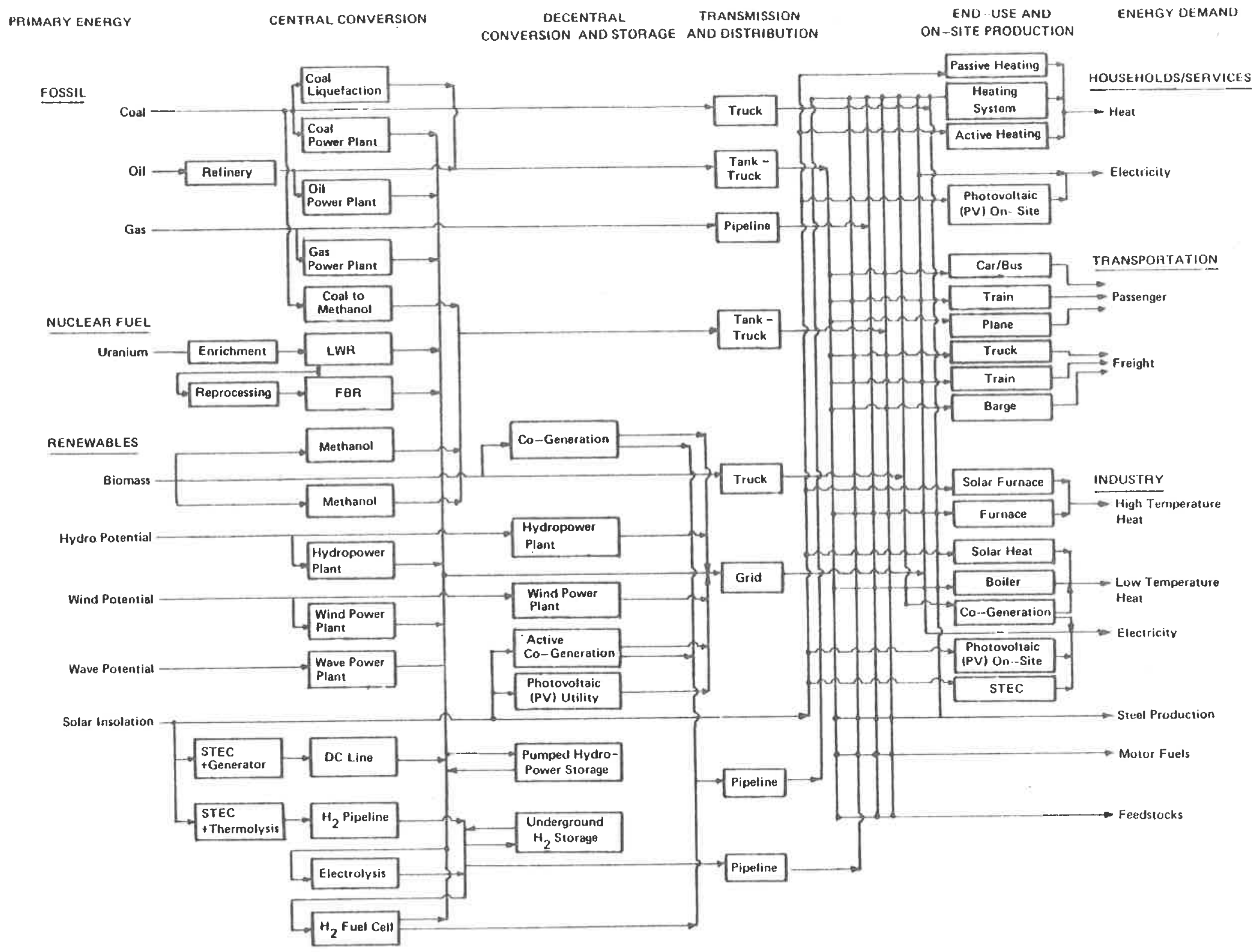

Figure 7.4. Energy system of the Soft Solar scenario.

Reference Systems and the Demand Projections

Let us briefly summarize those characteristics of the Hard and Soft Solar scenarios that have been considered up to this point. Both of the scenarios lead ultimately to sustainable energy supply as specified by the two future reference energy systems. The Hard Solar scenario relies primarily on the use of solar thermal and biomass potentials and the Soft Solar on on-site renewable energy and biomass, and to a lesser extent on local energy potentials. Only where these renewable sources of energy are not sufficient to meet the projected demands, is the solar thermal potential of South Europe integrated into the reference system. This preference for user orientation in the specified energy system of the Soft Solar scenario gives an early indication that the Higher energy demand projection might lead to serious supply problems if we rely only on the soft solar supply system. We have seen in Chapter 5 that the Higher demand projection implies greater use of liquid fuels (in transportation and industry) and greater low and high temperature heat requirements (in households/services and industry). In anticipation of the results presented in the next chapter we can state now that this additional demand for final and useful energy can be met only by using the centralized energy conversion, transport and distribution systems of the Hard Solar scenario. These, however, are "undesirable" (have low preference) in the Soft Solar scenario, and consequently this scenario corresponds to the Lower energy demand projection. For the Higher demand projection the Soft Solar scenario turned out to be inadequate--on-site and local renewable potentials are soon exhausted. On the other hand, the Hard Solar scenario appears to be mismatched with the Lower demand projection--the large-scale conversion and the long-distance transportation of energy is not required to the extent specified in its reference system. In this sense we consider the two scenarios as extremes, or two alternatives that delimit the range of possibilities. Assuming the Lower demand projection, the large centralized energy systems are simply not required on the foreseen scale. Assuming the Higher demand projection, the on-site and local systems are inadequate and become overshadowed by the requirements of a continental integrated energy system.

The scenarios are at least to an extent mutually exclusive since both of them require complete but different long-term efforts to restructure the current Western European energy system. Both of them require very intricate transition systems that combine the properties of the current and reference energy supply. Thus it is not foreseeable that the luxury of planning for both alternatives could be afforded throughout the transition period. Both systems require very high investment costs, high land requirements and so on (see Chapter 10). But in addition each of them implies a different supply system, a different structure of the economy (as was seen in Chapter 5) and drastic but different life-style changes.

Major Characteristics of Energy Technologies

Up to now we have outlined the structure of the energy systems of the two solar scenarios. We have illustrated the interdependencies of their various components both in the final state when the sustainable energy systems are achieved, toward the second half of the next century, and during the transition period from the current structure mainly dependent on the fossil energy sources. Figure 7.2, 7.3. and 7.4 have shown in schematic form the various conversion, transportation and distribution stages and links of the energy system between the resources and demand categories. In the following sections we will describe the performance and cost characteristics of each of these componets, starting from central conversion and ending with on-site conversion and end use systems.

Central Conversion Plants

Table 7.2 gives the cost assumptions for the conversion technologies used in the energy supply systems. Most of these conversion technologies use the energy resources in their primary form to convert them into secondary energy forms.

Typical of this class of conversion technologies are coal, oil and natural gas power plants. The cost and performance characteristics for these conventional power plants were taken

Table 7.2. Cost Assumptions for Energy Conversion Technologies

Technology	Capital Cost (1975$/kW)	Variable Cost[a] (1975$/kWyr)	Production Cost (1975$/kWyr)
Electricity Generation			
Coal Power Plant with Scrubber	550	23	246
Coal Fluidized Bed Power Plant	480	36	234
Oil-Fired Power Plant	350	19	340
Gas-Fired Power Plant	325	16	294
Gas Turbine Power Plant	170	17	335
LWR Power Plant	734	85[b]	182
FBR Power Plant	1000	118[b]	217
STEC Central Power Plant	1000	58	403
STEC Central Power Plant with Storage	3200	57	398
STEC Small Power Plant	2700	88	592
Central Solar Photovoltaic Power Plant	804	67	1067
Small Solar Photovoltaic Power Plant	625	105	482
Hydrogen Fuel Cell	54	11	450
Run of River Hydropower Plant	620	9	111
Pumped Storage Hydropower Plant	279	25	482
Large Wind Power Plant	344	14	117
Small Wind Power Plant	585	14	212
Wave Power Plant	1852	84	376
Liquid Fuels Production			
Crude Oil Refinery	50	4	105
Coal Liquefaction (Gasoline) Plant	480	40	180
Coal Methanol Production Plant	525	50	220
Biomass Methanol Production Plant	726	76	344
Biomass and Hydrogen Methanol Production	540	33	228
Hydrogen Production			
HTR Thermolysis Plant	764	24[b]	100
Solar Thermolysis Conversion Plant	710	33	278
Electrolysis Plant	36	10	307
Hydrogen-Storage	50	3	318
District Heat Generation			
Biomass Heating Plant	215	3	177
Active Solar Heating Plant	1703	30	212
Co-Generation			
Biomass Co-Generation Plant	720	22	211
Active Solar Co-Generation Plant	2720	101	291

a) Includes operating and maintenance costs without fuel costs. Fuel costs are included in the production costs.

b) Includes nuclear fuel cycle costs.

from the Global Study. Coal and gas need practically no treatment before they are either used in power plants or transported and distributed to end use as secondary fuel. Crude oil, however, is not used in its primary form. Instead, it is converted into a number of secondary energy forms in a refinery. We have used a rather simple model of the refinery producing one good: a mix of refinery products. Since the use of fuel oil would be eliminated before other refinery products during the transition period in the scenarios, refinery capital costs are assumed to be higher than at present due to additional cracking requirements.

The runoff river hydropower and light water reactor (LWR) plants are two additional electricity conversion technologies in extensive use today. The hydropower plants are assumed to be of a conventional design.

The LWRs are fueled by enriched natural uranium. During the transition period, before sustainable reference systems are fully implemented, more prudent use of the natural uranium resource is envisaged in the Hard Solar scenario. The spent LWR fuel is not discarded, instead it is reprocessed to recover plutonium converted from fertile uranium (U^{238}). This plutonium stockpile is used as the initial inventory in fast breeder reactors (FBR). The FBRs generate electricity by converting uranium (U^{238}) to additional plutonium or thorium to fissile uranium (U^{233}). The converted plutonium is used in turn to install new FBRs and fissile uranium to fuel either advanced LWRs (or high temperature reactors (HTR) in the Nuclear Scenario, see Chapter 9). This nuclear system is an efficient user of uranium resources and is used to enhance the transition from current, predominant use of fossil resources for electricity generation to future sustainable systems. The variable costs of all nuclear conversion technologies given in Table 7.2 include the fuel cycle (and reprocessing) costs.

The solar thermal electric conversion (STEC) power plants are assumed to be of the central receiver type. The centrally located tower contains the absorber and steam turbine generator rated at 10 to 100 MW(e) capacity. The central receiver tower is surrounded by a field of heliostats (two-apex tracking mirrors) that reflect and concentrate the direct beam solar radiation onto the absorber.

To improve the capacity utilization and decrease output variation, a STEC plant design with internal storage is also included. A high temperature thermal storage (salt or some other high temperature medium) is inserted between the aborber and the turbine-generator unit. In this way the performance can be improved and reaches a capacity factor of about 70 percent with thermal storage capable of delivering 12 hours of output at rated capacity. Of course, a similar effect can be achieved by using pumped hydro (underground or mountain reservoir) storage instead of the internal thermal storage facility. The cost and performance characteristics of the STEC power plants, with and without storage, were taken from Britt et al. (1979) and Selcuk (1975). In addition to the cost assumptions given in Table 7.2, Table 7.3 shows the performance assumptions of the STEC plants for the three insulation zones of South Europe.

In addition to the larger fossil, nuclear and solar thermal power plants, Table 7.2 includes a host of small electricity conversion technologies suited mainly for local and on-site electricity generation. Typical of this class of smaller conversion units based on renewable energy potentials is the photovoltaic electricity conversion. Two types of photovoltaic installations are considered, larger utility operated units and smaller user-oriented units that are installed on site of residential and commercial buildings and industrial facilities.

All photovoltaic units are assumed to be of a modular type, each module containing an array of photovoltaic cells with a solar radiation to electricity conversion efficiency of 15 percent. Considering the efficiency loss due to the assembly of single cells into modules and the possible need for direct to alternating current (DC to AC) conversion an overall efficiency of 11 percent is assumed for a given module. In order to increase the utilization factors, the modules are assumed to be mounted with a tilt towards south (on-site installations would also use the south-wall area). Finally, considering the differences in the solar radiation between the three parts of Western Europe (see Table 3.2), the overall capacity factor is 11.9 percent for installations in North Europe, 10 percent in Central and 16.5 percent in South Europe.

The investment costs, given in Table 7.2, are based on the assumption that the module cost would not exceed 500 \$(1975) per $kW(e)_{peak}$. The difference between the capital costs of utility and on-site units are due to other components, such as the support structure.

The larger of the two representative wind electric conversion plants is also assumed to be utility operated and the smaller is assumed to be user operated and installed in his vicinity. The utility plant consists of a number of horizontal

Table 7.3. Performance Assumptions of Solar Thermal Electric Conversion Plants, 100 MW(e)

	Performance in Insolation Zones[a]								
	Zone I			Zone II			Zone III		
Characteristic	DS	CR	CRS	DS	CR	CRS	DS	CR	CRS
Capacity Factor (%)	15.8	19.6	70.0	17.4	21.6	70.0	19.0	23.5	70.0
Area (km^2)									
Mirror	0.4	0.4	2.3	0.4	0.4	2.0	0.4	0.4	1.7
Land	1.0	1.4	7.7	0.9	1.4	6.5	0.9	1.4	5.5
Storage (hours)[b]	0	0	16.0	0	0	13.0	0	0	10.0

DS ... Dish Stirling
CR ... Central Receiver
CRS ... Central Receiver (Storage)

[a] For the characteristics of insolation zones see Tables 6.9 and 6.10.

[b] Storage in hours at rated capacity (100 MW(e)).

axis turbine units with a rotor diameter of 67 meters and a hub height of 50 meters (Meier and Merson, 1979). The units are rated at 1.5 MW(e) installed capacity and have an annual electricity generation potential of 580 kW(e)yr/yr per site at wind speeds exceeding 5 meters/second. The small-scale units for local use are also assumed to be of a horizontal axis machine design (M.A.N., 1979) with a rotor diameter of 11 meters and a hub height of about 10 meters. The annual electricity generation potential is about 2 kW(e)yr/yr per unit at wind speeds exceeding 5 meters/second.

We have assumed that the wind power plants can supply at most 30 percent of total electricity demand without a serious generation and demand load profile mismatch. This share can be substantially increased (perhaps by another 30 percent) if daily electricity storage facilities are used. As was already mentioned above, the pumped hydropower storage facility is foreseen for daily generation and demand balances. This means that a part of the electricity generation in STEC, photovoltaic, wind and wave power plants is delivered to final use via hydro storage.

Wave power plants are the least competitive of all renewable electricity conversion facilities. They consist of a number of 10 meter long buoys anchored off-shore. The electricity generating capacity is estimated at 180 MW(e) per site. As can be seen from Table 7.2, the capital costs are very high and capacity utilization is assumed to be at most 55 percent, so that the electricity production costs exceed those of the wind electricity conversion plants. Expected life time of wave power plants is about 20 years.

We have already described the simple refinery used as a representative current liquid fuels conversion technology. More advanced coal to liquid fuels conversion technologies are also included in the scenarios (as can be seen from the schematic representation of the energy system from Figures 7.3 and 7.4), although they are not a part of the reference energy systems which rely exclusively on renewable potentials. However, liquid fuels production from coal is necessary in order to replace refinery products during the transition period before coal liquid fuels themselves are substituted by (biomass) methanol and (solar) hydrogen. The advanced coal technologies include autothermal liquefaction and later also methanol synthesis in order to enhance the transition to methanol as a major liquid fuel in the reference systems. Ultimately, all hydrocarbon fuel demands (mainly for non-energy uses, i.e. feedstocks) would be delivered by methanol generated from biomass. The production processes are based on biomass gasification to break the cellulose and then synthesize methanol under pressure. Basically this means that the hydrogen to carbon atom ratio of biomass of about 1.7 has to be increased to over four in order to synthesize methanol. We have considered two possible technologies. In the first case the ratio is increased by releasing carbon dioxide from biomass during the gasification step. In the second process the carbon dioxide is retained and biomass is blended with additional hydrogen to generate methanol. In the sustainable system the hydrogen blending process is used exclusively in order to enhance the use of biomass as a source of carbon atom. Hydrogen, on the other hand, is assumed to come from a number of different sources.

Initially, the electrolysis plant plays the equivalent role as the coal to methanol synthesis plant. It represents an advanced version of a technology that is available today, but not needed in the sustainable energy system. It is required, however, to alleviate the transition to wide-spread use of thermolytic hydrogen produced in the solar thermal plants.

Hydrogen is foreseen as a preferential form of secondary energy not only because it can help to economize the use of the carbon atom from biomass, but also because it is easier to transport over long distances and store over longer periods than electricity. Initially hydrogen is assumed to be produced by eletrolysis of water, but later direct thermolytic splitting of water would be used without electricity as an intermediate step. In the Nuclear scenario (described in Chapter 9) also high temperature reactors (HTR) would produce thermolytic hydrogen.

Today it may appear doubtful whether such advanced technology would be soon available and competitive with electrolysis. We anticipate very favorable costs for thermolytic hydrogen production by assuming that the current research and development of the HTR would lead to new technological break-throughs for the future (50 years or so) that are also applicable to STEC plants.

We have mentioned that hydro storage facilities are foreseen to balance the daily electricity generation and demand load profiles. The preferred location of these storage facilities are the underground, already mined rock caverns and the high mountain reservoirs so as to minimize the construction and scenic impacts. Hydro facilities, however, are not suited for seasonal storage due to large storage volume requirements. Since hydrogen is assumed to be a preferential energy form, it is foreseen that hydrogen storage would be used to complement electricity in balancing the seasonal generation and demand differences. Hydrogen would be stored in depleted gas and oil fields of Western Europe. Such underground formations are especially suited for storage since they previously contained gas and fluids at high pressures and have been connected to Western European pipeline grids. Thus a new infrastructure would not be needed, only an upgrading of the already existing infrastructure would be required. Consequently, capital costs are also assumed to be relatively low in Table 7.2. Additional daily hydrogen storage is assumed not to be required since the long-distance hydrogen pipelines from South Europe, where the STEC plants are located, have a sufficiently large volume to act as daily storage when the hydrogen pressure is varied by up to 10 percent.

The "indirect" seasonal storage of electricity is achieved by using the fuel cells to convert hydrogen to electricity. We have assumed an efficiency of about 70 percent and in addition the possibility of using the waste heat for district heating purposes.

For the generation of low to medium temperature heat biomass and active solar district heat and co-generation plants can be used in addition to the hydrogen fuel cells. The biomass co-generation plants are assumed to be rated at 300 MW(e) installed capacity and the smaller district heat plants at 50 MW(th) installed capacity. The active solar district heat plant is operated during the winter using seasonal heat storage (rocks or some other high temperature medium). The use of the solar co-generation plants is limited to South Europe due to relatively high solar insolation levels, but nevertheless they still need on the average a 60 percent back-up capacity (30 percent in summer and 70 percent in winter time). Biomass is used as a back-up fuel.

Energy Transportation and Distribution Systems

The transportation of solid and liquid fuels is limited to road and rail. Although other alternatives exist, such as barge and oil and coal slurry pipeline, they are assumed not to be used so extensively for energy transportation to warrant separate treatment. To the extent that these are used, their costs are included under truck and rail transportation in Table 7.4. A typical unit train is assumed to contain either tank cars for liquids or steel bed cars for solid transportation. 10 percent of spare cars and 7.5 percent of spare locomotives are foreseen as maintenance back-up capacity and are included in capital costs. The trains are rated at about one billion ton-kilometers per year capacity and have a life time of about 20 years.

The trucks are of the over-the-road, semi-rig type capable of transporting 25 tons of solids or liquids at an annual capacity of about 2 million ton-kilometers. The expected life time is seven years.

Electricity and gaseous secondary energy is distributed to end users by grids. The electricity grid consists of a network of areal lines connecting the long-distance transmission links and power plants with end use devices. A small number of underground lines is assumed in very densely populated areas. The costs given in Table 7.4 are based on a sub-grid unit capacity of 132 MW(e). The expected life time is 50 years.

The natural gas or hydrogen distribution grids include the main and secondary stations, metering and control equipment and secondary lines. The grid connects the long-distance pipelines with end use devices. The costs are based on a sub-grid capacity of 0.6 GW(th) of natural gas or hydrogen. The expected life time is 40 years. Although hydrogen has three times lower specific energy content at given pressure than natural gas, the costs are the same, because hydrogen flows about three times faster through a pipeline than natural gas at the same pressure (Beghi et al, 1972).

Table 7.4. Cost Assumptions for Energy Transportation and Distribution Systems

Transportation System	Capital Cost (1975$/kW)	Variable Cost (1975$/kWyr)	Transportation Cost[a] (1975$/kWyr)	Efficiency (%)
Truck or Rail				
Coal	18	15	19	95
Oil	23	10	15	98
Biomass	31	15	22	95
Methanol	23	23	28	98
Distribution Grid				
Electricity	330	6	19	85
Gas	120	4	13	90
Hydrogen	120	4	13	90
Transportation Links[b]				
DC Electricity	(130-260)	(0.7-1.3)	(10-20)	(96-92)
Hydrogen Pipeline	(121-239)	(1.2-2.4)	(10-19)	(98-96)

a) Production costs are not included, but efficiencies are accounted for.

b) Values in parentheses: First value for transportation links to Central Europe and second to North Europe.

SOURCE: Bechtel National, Inc. (1978).

The costs of long-distance electricity and hydrogen transportation links from South to Central and North Europe are also given in Table 7.4. Figure 7.5 illustrates possible long-distance links for Western Europe. Distances between nodes are assumed to range from about 1000 to 2000 kilometers. Electricity is transported by 800 kV direct current (DC) transmission links with an overall efficiency in excess of 90 percent. Step stations and rectifiers are included in this estimate, the life time of a given link is about 50 years. The hydrogen pipeline is an advanced large volume high pressure design with a diameter in excess of one meter. It also acts as daily hydrogen storage facility through about 10 percent pressure variations. The estimates include the cost of compressor stations. The expected life time of a given link is about 40 years.

Energy End Use in Transportation

The energy demand projections for Western Europe, presented in Chapter 5, were assessed for all sectors in terms of useful and final energy requirements. The main exception were the projections for the transportation sector (which does not include energy transportation requirements discussed in the last section). There we have mentioned (on p. 77) that the energy use in transportation does not only depend on the distribution of different transportation modes and their respective usage, but also on the energy intensities per traveled person-kilometer or transported ton-kilometer. These intensities are a function of vehicle efficiency, capacity utilization, traffic flow and structure, and the types of fuel used. Thus, considering the capacity utilization and traffic system characteristics, we have presented a projection of different transportation service requirements (in Chapter 5). Here we will state our assumptions about the energy intensity of different transportation modes and their costs. Given this information, the energy requirements for non-energy transportation can be determined within the overall energy system structure outlined by the scenarios.

Table 7.5A gives the specific energy requirements (in 1975) per transported ton-kilometer and traveled vehicle-kilometer of different transportation modes, and the relative energy

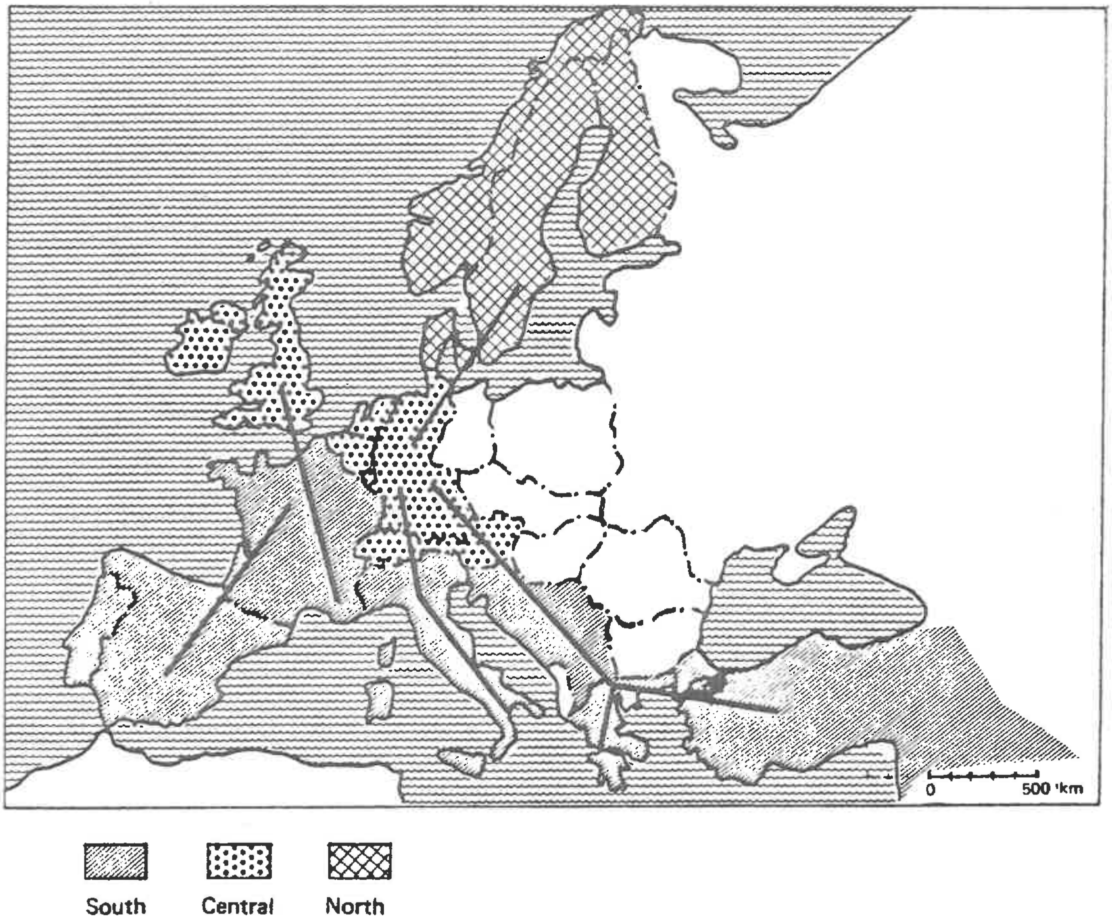

Figure 7.5. Possible hydrogen and electricity transportation links

Table 7.5A. Cost Assumptions[a] of Freight and Passenger Transportation Modes Using Fossil Liquid Fuels

Mode	Capital Cost	Variable Cost	Energy Use[b] Intensity	Energy Use[b] Relative Decrease
Freight	(1000 1975$/vehicle)	(1975$/1000 ton-km)	(Wyr/1000 ton-km)	(%)
Truck	70	30	80	(35-51)
Train	8800	9	33	(40-51)
Barge	5600	1	40	(35-36)
Passenger	(1000 1975$/vehicle)	(1975$/vehicle-km)	(Wyr/100 vehicle-km)	
Car	8	0.01	11[c]	(52-74)[c]
Bus	60	2.80	40	(45-57)
Train	800	16.80	265	(22-40)
Plane			9[d]	(43-65)[d]

a) The assumptions are based on the use of fossil liquid fuels. Table 7.5B gives the conversion factors for other alternative fuels.

b) Final Energy intensities in 1975 and relative decrease by the year 2100 in percent of the 1975 levels: First value for the Hard Solar and second for the Soft Solar scenario (see Table 5.13).

c) Corresponds to an average fleet fuel consumption of 13 l/100 km.

d) For air travel the intensity is given in Wyr/100 seat-km.

intensity decreases for the two solar scenarios, assuming further use of fossil fuels. As we have mentioned in Chapter 5 (see also Table 5.13), significant improvements in freight and passenger transportation efficiencies are postulated. The efficiency improvements results from higher capacity utilization (i.e. relatively lower vehicle-kilometer activity levels compared with person-kilometer projections) and from lower energy intenstities. Highly optimistic energy efficiency improvements are shown for passenger (urban and intercity average) car and plane travel. The specific energy requirements are reduced for these two transportation modes by up to 70 percent, while for other modes of passenger and freight transportation the improvements range roughly between 30 to 40 percent.

Table 7.5A also gives the capital and variable costs based on the further use of fossil fuels. The apparently large differences in costs of various transportation modes are important indicators of the different roles that they fulfill within the transportation system. For example, the variable cost of freight transportation by truck is significantly higher than the cost of train or barge. However, truck transportation is much more flexible and faster and in addition the only practical mode of urban freight delivery. The factors that determine the relative shares of different transportation modes have been discussed in Chapter 5 within the assessment of the energy services requirements in the transportation sector.

The specific energy requirements of different transportation modes given in Table 7.5A for fossil fuels could be fulfilled by a number of final energy forms that are modeled in the sustainable supply systems of the two scenarios. Table 7.5B gives the relative cost and energy intensity changes for alternative (non fossil) fuels. Fossil fuels cost and energy intensity is taken to be normalized to unity in this table. It is shown, for example, that for cars the fuel requirements (per vehicle-kilometer) would be lower for methanol and hydrogen than for gasoline, but that capital costs would increase due to more complex fuel storage (tank) and energy conversion requirements (engine, fuel system, etc.). Variable costs are also lower largely due to lower environmental and other impacts of these

Table 7.5B. Cost and Energy-Use Assumptions of Freight and Passenger Transportation Modes Using Alternative Fuels[a]

Fuel	(Fossil Fuels Factor = 1)[a] Capital Cost	Variable Cost	Energy Use
Car			
Gasoline	1	1	1
Methanol	1.1	0.75	0.83
Hydrogen	1.2	0.75	0.59
Bus, Truck, Barge			
Diesel	1	1	1
Methanol	1	0.7	1.2
Hydrogen	1.2	0.7	0.77
Train			
Diesel	1	1	1
Electricity	1	0.8	0.33
Hydrogen	1	0.8	0.67
Plane			
Jet Fuel	1	1	1
Hydrogen	0.7	1	0.54

a) All numbers are expressed relative to cost and energy use for fossil liquid fuels (factor = 1), see Table 7.5A.

fuels (e.g. the engine oil is cleaner when methanol or hydrogen are used which implicitly leads to longer service intervals). Similar reasoning was used in deriving the cost and energy intensity requirements for other transportation modes. Finally, it should be observed that capital costs of a hydrogen airplane are lower than those of a conventional one, since the specific weight of hydrogen per energy unit it can deliver in a jet engine is lower, leading to a singificantly lower weight of the aircraft.

Energy End Use in Other Sectors of the Economy

The energy use and costs of various transportation modes represent only one category of energy end use devices and facilities. Within the framework of the Higher and Lower demand projections we have presented the final and useful energy requirements of all other sectors in addition to the energy service requirements of the transportation sector. In all sectors the projected energy demands were a function of many energy use determinants, but as the most important we have specified the implied life-style changes and structural changes, and efficiency improvements. The resulting specific energy use requrirements are used within the energy supply system to determine the substitution between different energy forms and various components of the energy system necessary for satisfying the specified energy demands. In particular, we have seen that given the required vehicle-kilometer and ton-kilometer transportation requirements, various fuels could be used in various transportation modes to deliver this energy service. The choice of a given fuel, however, would depend on the particular energy system configuration. A similar consideration also applies to the energy end use in other sectors. In addition, in all sectors except transportation we have also foreseen the possibility of on-site generation within the Soft Solar scenario. This increases the complexity of the energy end use systems. Namely, it is also possible to use on-site energy generation for supplying a given energy demand instead of only choosing a particular end use device with a given final energy form.

Table 7.6 gives the cost and performance assumptions for energy end use in agriculture, construction and manufacturing for the major energy end use categories specified in the two energy demand projections of Chapter 5. Table 7.7 gives the cost and performance assumption of energy end use technologies for space and water heating in households and services. Since many of these end uses and technologies are not available today, the earliest foreseeable date of commercial utilization is also given in Tables 7.6 and 7.7. The energy use and technologies range from the conventional oil burner and heat pumps to advanced conversion devices such as on-site STEC in industrial use of solar-thermal high temperature heat.

Within the two demand projections of Chapter 5 all water heating, steam generation, furnace (high temperature) heat and space heating requirements have been specified in terms of useful energy. These use categories represent the last level of the energy system as was shown in the schematic structure of the energy systems in Figures 7.3 and 7.4. Thus these energy use categories represent an interface between the energy supply system and energy demands resulting from economic and other human activities. At this interface the energy available for final uses is the actual amount of different final energy forms. Thus, the efficiencies given in Tables 7.6 and 7.7 for these four end use categories represent the conversion of final to useful energy. Within each of these four categories any given final energy form can be used to deliver the demanded useful energy. Which one is chosen depends on the overall structure of the energy system (e.g. energy availability, costs, etc.).

The specific electricity requirements, however, are basically (by definition) not substitutable by other forms of final energy. For space and water heating, however, a host of technologies can be used. We have limited our consideration of the end use devices (for all sectors) to the components specific for a given technology and have exluced those components common to all end use devices. For example, the costs of space heating systems include only the parts relevant to the given form of final energy (e.g. gas, oil, methanol, hydrogen, electricity and active on-site solar) such as the burner itself, fuel or heat storage,

Table 7.6. Cost and Performance Assumptions for Energy End Use in Agriculture, Construction and Manufacturing

Energy End Use	Capital Cost (1975$/kW)	Variable Cost (1975$/kW)	Efficiency (%)[a]	Plant Factor (%)	Introduction Date (Year)
Thermal Low					
Coal	100	15	85	70	1975
Oil	38	6	89	70	1975
Gas	30	5	90	70	1975
Biomass	120	30	85	70	1980
Methanol	38	6	89	70	1990
Hydrogen	30	6	100	70	2010
Electricity	120	3	95	70	1975
Solar-Thermal (low)	1011	76	n.a.	40	1995
Thermal High					
Coal	550	17	60	100	1975
Oil	500	15	60	100	1975
Gas	450	14	60	100	1975
Methanol	500	15	60	100	1990
Hydropower	450	14	100	100	2010
Electricity	400	12	100	100	1975
Solar-Thermal (high)	1311	98	n.a.	40	2010
Steel Production					
Coal (Coke)	1000	30	75	100	1975
Gas	500	15	100	100	1980
Methanol	500	15	100	100	1990
Hydrogen (and Coal)	500	15	135	100	2010
Feedstocks					
Oil			100		1975
Gas			100		1975
Methanol			100		1990
Motor Fuels					
Oil			100		1975
Gas			100		1975
Methanol			120		1990
Hydrogen			200		2010
Electricity					
On-Site Photovoltaics	625	157	12	12	2010
On-Site STEC	2704	203	40	40	2010
Co-Generation					
Coal	690	24	87	85	1975
Biomass	569	34	82	50	1995

[a] (n.a. - not applicable).
The efficiencies for coke, feedstocks and motor fuels indicate the relative performance of alternative fuels with respect to coal for coke, and oil for feedstocks and motor fuels. Since these fuels are directly used in these three energy use categories without prior conversion the capital and variable costs are not given.

Table 7.7. Cost and Performance Assumptions for Energy End-Use Technologies in Households and Services

Technology	Capital Cost (1975$/kW)[a]	Efficiency (%)[b]	Plant Factor (%)	Introduction Date (Year)[c]
Water Heating				
Oil Burner	59	57	15	1975
Gas burner	127	60	15	1975
Methanol Burner	59	60	15	1995
Hydrogen Burner	127	100	15	2025
Electric Boiler	123	95	15	1975
Active Solar	1396	n.a.	50	1995
Space Heating				
Coal	27	55	20	1975
Light Oil	42	65	20	1975
Natural Gas	23	70	20	1975
Biomass	33	55	20	1975
Methanol	42	70	20	1995
Hydrogen	23	100	20	2025
Electricity	20	95	20	1975
Heat Pumps	77	300	20	1980
Passive Solar	2639	n.a.	20	1995
Water and Space Heating				
Active Solar	1326	n.a.	20	1995
Electricity				
On-Site Photovoltaics	625	12	12	2010

[a] Fix operation and maintenance costs range between 1 to 3 percent of capital cost per year.

[b] n.a. - not applicable.
Heat pump efficiency of 300 percent refers to coefficient of performance.

[c] Already available systems are introduced in the base year (1975).

connection to grid or local energy transport and so on. The parts common to all space heating systems are not included: distribution system within the building (pipes), radiators, thermostats, etc.

The coal, oil, gas and electricity heating devices and heat pumps are all available today. Biomass (mainly fuel wood) is also used in Western Europe, but current use is limited to a few rural areas. The biomass heating envisaged in the scenarios is based on pre-processed biomass that has qualities of other commercial fuels (it is compressed to energy densities of brown coal). Thus the efficiencies of biomass heating systems are as high as those of burning coal, but costs are higher due to more elaborate fuel handling. The use of methanol and hydrogen in heating systems and extensive solar heating are new technologies. We have assumed that these fuels would provide similar efficiencies and performance similar to current liquid (oil) and gaseous (natural gas) fuels. The performance and costs of solar heating systems are qualitatively different from current heating devices. These systems do not simply convert final into useful energy, they generate useful energy on site. In addition, their effective application necessitates a new design or substantial modification of the building and usually also requires some kind of back-up capacity or storage system. Fortunately, relatively high reductions of energy for space heating were possible in both demand projections (see Tables 5.14 and 5.15 in Chapter 5), due to very high insulation of buildings, so that additional insulation requirements for solar heating are not very elaborate. This tends to reduce the already high investment costs of solar heating systems. In particular, the only additional insulation needed to convert a very efficient house of the Lower demand projection into a passive solar house is the exterior glazing and framing on the south wall, movable shutters to retain the collected heat during the night, heating vents in the wall area and suitable materials to ensure good absorption and wall stability at higher temperatures. Only these costs are included in the estimates in Table 7.7. The capital costs of 2639 \$(1975)/kW is an average figure for Western Europe (the capital costs are in fact 14 percent lower in South than in Central Euorpe). The estimates are based on the analyses of monthly mean global solar radiation and air temperatures at representative sites of Western Europe.

The costs and performance of the active solar systems have been assessed by an equivalent procedure. The basic additional components are the non-concentrating solar heat collectors that operate at moderate temperatures. The capital costs are lower since some of the additional insulation is not required. All of the solar heating capital costs (for both passive and active systems) have in addition the cost of back-up capacity. The cost estimates of all solar systems are based on the work for an earlier report to the BMFT (Bell et al., 1978).

The specific electricity requirements (Table 5.16B) of households and services are assumed to be provided by the grid and some use of on-site photovoltaic and wind electricity conversion. These systems were previously discussed under the section on central conversion technologies above.

The generation of useful heat and specific electricity for agriculture, construction and manufacturing (see Tables 5.9A and B and 7.6) employs all end use devices described above except passive solar space heating. The specific electricity requirements can be partially fulfilled by on-site generation from small STEC plants with heat storage and on-site photovoltaic arrays. These on-site electricity generation systems do not include the costs of the back-up, since the connection to the grid with a sufficient capacity is assumed whether on-site generation is used or not. The small STEC plant can also be employed directly for production of furnace and low temperature (process) heat. Finally, small coal and biomass co-generation plants can also be used.

The specific final energy needs such as current uses of coke for steel production, petrochemical products as feedstocks and motor fuels are assumed to be fully substitutable by hydrogen and methanol in Table 7.6.

These categories of energy end use have been expressed in terms of final energy in the two demand projections of Chapter 5. Therefore, the efficiencies indicate the relative performance of alternative fuels with respect to coke (from coal) uses, oil use for feedstocks and motor fuels. For example, the use of hydrogen (with two percent coal as a source of carbon) for steel production implies a relative performance improvement (efficiency) factor of 1.35. In terms of final energy requirements for coke this means that 74 percent less hydrogen is required than coke. The use of methanol for feedstocks causes the same final energy requirements as the use of oil products. The use of methanol and hydrogen for motor fuels, on the other hand, implies lower final energy requirements than the use of gasoline and diesel fuels (13 percent reduction for methanol and 50 percent reduction for hydrogen use).

We have seen that a variety of energy supply technologies can compete within the energy system to meet demands. However, a change in the sources of primary energy usually leads to different energy end use patterns. In some cases such structural changes of the energy system lead to higher final energy requirements for a given useful energy demand and in others to lower requirements. However, the actual energy flows and balances throughout the energy system are not only a function of the substitutability between various energy forms and technologies, but also of technological development and cost structure changes of various fuels and technologies.

Build-Up Rates of Technologies

We have seen that the energy supply systems of the two solar scenarios employ a host of new technologies assumed to become commercially available during the next 100 years. The use of the new technologies and those already available today is limited locally and in Western Europe by the magnitude of resources, renewable potentials and the opportunities of additional energy imports.

These limitations have been specified in the previous chapter. Their assessment was based not only on the absolute magnitude that might eventually become available but also considering the various constraints, such as competitive land use. We have also mentioned that the specified potentials of new and traditional resources can be exploited only under the condition that much time be allowed for the full introduction of new technolgies and that anticipated structural changes in the Western European economy take place. In this chapter we have addressed the required structural changes of the energy system that would result after the transition period in a sustainable energy supply of the two reference systems. The dynamics of these structural changes is limited by the maximum build-up rates of new technologies. Table 7.8 gives the assumed build-up rates for energy conversion, transportation and end-use technologies. They do not exceed the historical build-up rates of today's energy technologies given in Table 6.18. In addition, the start-up capacity given in Table 7.8 indicates the level at which a technology is assumed to become commercially available. Together the build-up rates and start-up capacities determine the maximum asymptotic growth of any technology, with higher growth rates at the beginning. As a general feature, the build-up constraints are more stringent for end use technologies, reflecting typically greater complexity of such systems. It is relatively easy to construct one solar heated house, but a large-scale construction effort requires an elaborate supporting

Table 7.8. Build-up and Start-up Constraint Assumptions for New Energy Technologies

Energy Technology	Build-up[a] Rate (%/yr)	Start-up[b] Capacity (MW)
Conversion	15[c]	300
Transportation and Distribution	15	900
End-Uses	7	n.a.[d]

[a] Build-up rate is the maximal exponential growth of a new technology.

[b] Maximal installed capacity in the introduction year of the new technology.

[c] Build-up rate constraint for nuclear conversion technologies was assumed to be 8.4 percent per year due to relatively favorable costs of this technology.

[d] Not applicable. Start-up constraint for every end use technology was specified at 0.1 percent of the demand class it serves.

infrastructure and an active participation of the energy consumer. However, the build-up rate constraints provide only an upper limit to the introduction rates: The actual introduction rates depend on other factors, one of the most important of them being the relative costs of competing technologies.

Cost Assumptions

The assumptions used in this chapter for assessing the capital and variable costs of competing technologies are highly judgmental in spite of the fact that they were arrived at by averaging and comparing many different data sources. And while these costs will surely change over time, perhaps dramatically, just one cost estimate for each technology was given for the entire time horizon of 120 years. Thus the possibility that the cost figures given in previous sections might be greatly understated should not be overlooked. It can be observed today that the real costs of complex energy supply systems invariably exceed expectations, and this may not change in the future. This possibility could well strengthen interest in the potential economic attractiveness of energy efficiency improvements (or energy productivity increases) that have been assumed in the two energy demand projections in Chapter 5. The cost estimates used in this chapter for the energy system are, for better or for worse, no more than a composite of the best estimates.

We have already seen that the two energy supply reference systems of the Hard and Soft Solar scenarios represent a radical restructuring of the energy system in order to provide sustainable amounts of required energy after a long transition period. Therefore it is by no means obvious how such an energy system could be achieved even in the long run by relying exclusively on market forces and international trade opportunities. Governmental regulations and interventions alone are probably also not sufficient to assure such a transition to sustainable systems. Clearly it would be possible to impose in a model additional physical constraints on the energy system that would force the desired structural changes. This approach would be similar to the procedure we have used in the previous chapter of explicitly observing physical and environmental constraints in the assessment of energy resources and potentials. However, the imposition of such explicit limitations on the energy system necessarily leads to a host of complex political and social issues that we can not assess today. At the same time it is not clear if such limitations could even be agreed upon and which mechanisms could translate them into operational regulations that limit the structure of the energy system. A simple moratorium on one particular energy source or form clearly does not lead to the desired result. In particular, partial moratoriums would be required for many technologies starting with energy conversion and going all the way to end use. Other desirable technologies would have to be supported. Finally, we should state that such a procedure is only feasible in a model if limitations are considered for each specific technology and then for the energy system as a whole, requiring a very elaborate and sensitive iterative approach that may not necessarily lead to the specified reference systems. Thus, due to these difficulties of interpreting the required limitations leading to a given system structure, and the difficulties of actual implementation of the limitations in a model, we have chosen an alternative approach that leads to a consistent energy system structure. We have specified relative changes in costs of different energy technologies, favoring renewable energy systems. These differential costs can be easily interpreted--they correspond to taxes or cost penalties levied on systems that are not desirable in the long run, but necessary during the transition period. It is conceivable that the revenues resulting from such taxes could be used to cover the development costs of new technologies or even for transfer payments for already introduced new technologies that are not fully competitive.

Our scenarios were not intended to be predictive or descriptive of a likely energy future of Western Europe. We have attempted to design two extreme energy systems and to outline the corresponding energy demand and economic implications. Now we will show that changes in relative costs of energy technologies are also required for the implementation of a sustainable system and that they are different for the two scenarios. Table 7.9 illustrates our assumptions that lead, after the transition

Table 7.9. Relative Capital and Fuel Cost[a] Increases of Energy Conversion, Transportation and Distribution Technologies (Factor Increases Relative to Base Year Cost[b])

	Scenario			
	Hard Solar		Soft Solar	
Technology	2030	2100	2030	2100
Fossil and Uranium Resources	3.4	19.4	3.4	19.4
Fossil Conversion	1.6	3.3	1.6	3.3
Nuclear Conversion	3.4	19.4	3.4	19.4
Solar-Thermal Conversion	1	1	1.8	1.8
Biomass Conversion	1	1	1	1
Hydropower	1	1	1	1
Other Renewable Electric[c]	n.a.	n.a.	0.6	0.6
Transportation and Distribution	1	1	1	1
Small Conversion Plants	1	1	0.6	0.6
End Use Devices	1	1	1	1
On-Site Renewables	n.a.	n.a.	0.4	0.4

a) A 6 percent annual discount rate and a 0.5 percent annual real cost increase were imposed on all technologies. A cost factor increase of 19.4 over a period of 125 years corresponds to an annual cost increase of 2.4 percent per year.

b) All numbers represent factor cost increases relative to capital and fuel costs in the base year 1975, see Tables 7.2, 7.4, 7.5, 7.6 and 7.7.

c) On-Site and Other Renewable Potentials (e.g., wind and wave power) are not used in the Hard Solar scenario.

period, to the sustainable systems. The relative cost increases of fossil and nuclear energy are greatest in both scenarios. A relative almost 20-fold cost increase over the 1975 level is assumed (corresponding to a 2.4 percent annual increase). On the other hand, in the Soft scenario the wind power and small conversion plants are assumed to have relatively lower costs. The most drastic cost differentials are assumed for on-site renewable energy sources, such as passive and active solar heating and photovoltaic roof collectors. Finally, we should also observe that a 6 percent annual discount factor and an additional 0.5 percent real cost increase were used for all components of the energy system for the entire time horizon.

In conclusion, the general approach in the scenarios is that a variety of energy conversion, transportation and distrubiton technologies can compete to meet demands. 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 new facilities 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 differential cost changes they can be seen as deliberate planning of 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 two scenarios represent extreme future solar 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. In a sense, all of the constraints imposed in our analysis, taken together, are the singular characteristic of the scenarios. In the next chapter we will present the actual results for the two scenarios, showing the results of this constrained competition within the energy system that is consistent with the assumed evolution of the economic and energy demand structure.

8. ENERGY DEMAND AND SUPPLY IN THE SCENARIOS

Energy Balance

In Chapters 5 through 7 we assessed the future energy demand of Western Europe and the economic and life-style changes that are consistent with the Higher and Lower demand projections. We explored the potentials of different energy options and the constraints that could limit the extent to which those potentials could be exploited. Finally, we outlined the structure of energy conversion, transportation and distribution systems capable of delivering the demanded energy under the limitations of technological and resource constraints. All these aspects of the future energy outlook for Western Europe, together with cost considerations, result in a quantitative balancing of energy demand and supply that leads to a truly sustainable energy system built around non-depletable resources.

In this chapter we will show how such a balance is achieved within the energy systems of the Hard and Soft Solar scenarios. Thus the material in this chapter is complementary to that of the previous chapters. The two previous chapters sought to explore the bounds of the possible, this chapter balances the constraining factors to identify the limits of the plausible. The Hard Solar scenario represents the limit on energy demand and supply from centralized solar energy systems and the Soft Solar scenario the limit on energy demand and supply from local and on-site energy systems. The purpose of the two scenarios is to detail realistically the consequences that might follow from the assumptions. The results should be interpreted carefully since the scenarios do not represent predictions of a likely evolution of the Western European energy system. On the contrary, they outline two consistent evolutions based on two sets of assumptions. Thus the detailed description of the assumptions in previous chapters must be viewed together with the energy balances of this chapter as a synthesis of our scenario approach. The quantitative energy balances represent the qualitative changes necessary to achieve sustainable energy systems. Thus the significance of the numerical results is important as a guarantee for consistency, however the central feature of the scenarios are the qualitative changes implied by the numerical results.

Summary of the Results

It will be impossible here to describe in full detail all of the results of energy balancing performed in the MESSAGE II model. This is apparent when the complexity of the energy systems described in the previous chapter is considered. Instead, we will present the quantitative results by considering the evolution of the scenarios at carefully chosen intersections and links of the energy system, such as liquid fuels supply or installed capacities of electricity conversion plants. It should be emphasized that the balances are cost optimal under the constraints and limitations we have presented in previous chapters.

Recalling the schematic diagrams of energy systems from Figures 7.3 and 7.4, the first such intersection is the primary energy supply. Table 8.1 and Figure 8.1a show the primary energy use from 1975 to 2100. It increases almost four-fold in the Hard Solar scenario and more than two-fold in the Soft Solar scenario. The next obvious intersection is the final energy use that results after the primary energy is converted into more convenient energy forms and fuels, transported and distributed to the final user. Table 8.1 and Figure 8.1b also show the final energy use from 1975 to 2100. Here, due to conversion losses the increases are not as large as was the case for primary energy. In fact, the final

Table 8.1. Primary and Final Energy Use (TWyr/yr)

	Base Year	Scenario			
Energy Form	1975	2000	2030	2060	2100
Primary					
Hard Solar	1.53	2.29	3.20	4.47	5.76
Soft Solar	1.53	1.84	2.36	2.75	3.16
Region III[a]	2.26	3.39	4.54		
World[a]	8.21	13.59	22.39		
Final					
Hard Solar	1.19	1.52	1.82	2.20	2.81
Soft Solar	1.19	1.26	1.17	1.27	1.39
Region III[a]	1.59	2.39	2.99		
World[a]	5.74	9.64	14.56		

a) Global Low scenario.

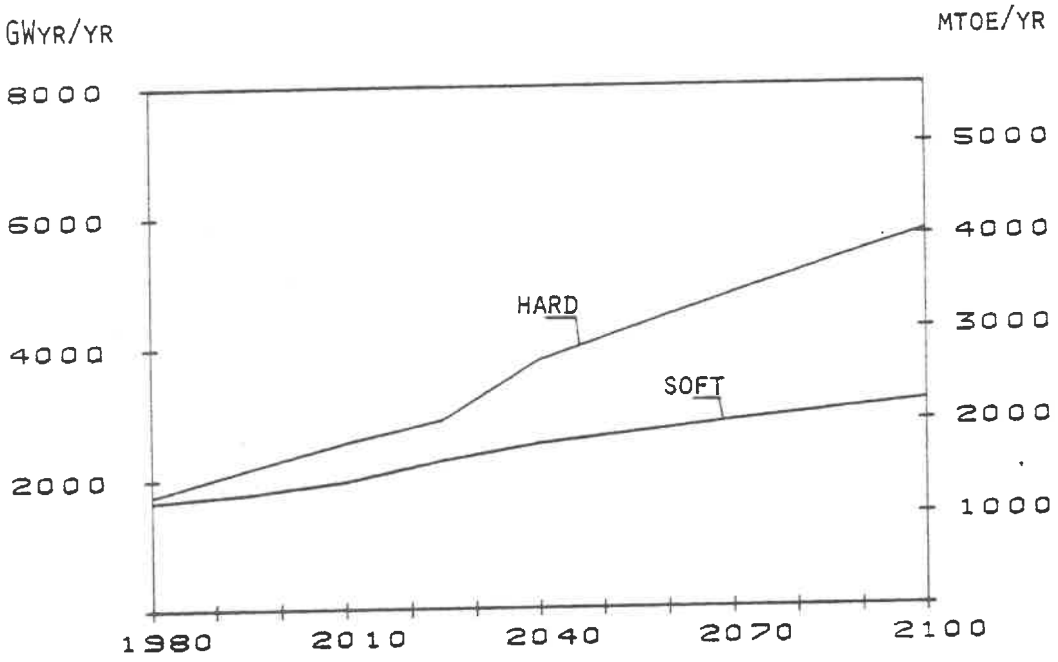

Figure 8.1a. Primary energy, Hard and Soft Solar scenarios.

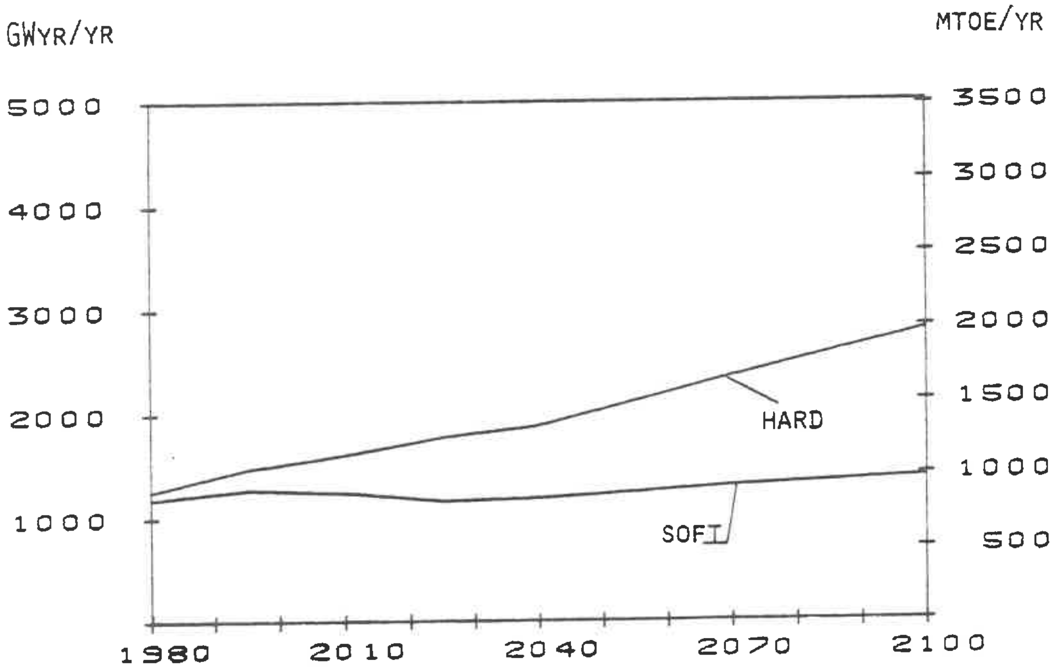

Figure 8.1b. Final energy, Hard and Soft Solar scenarios.

energy use stays almost constant with respect to the 1975 level in the Soft Solar scenario, and increases more than two-fold in the Hard Solar. But even the primary energy increases are modest considering the long time horizon of over 100 years. During the 25 year period of 1950 to 1975 the primary energy use increased by a factor of 2.5--an increase larger than in the Soft Solar scenario by the year 2100. In the scenarios the low energy growth was only possible due to the strong change of economic structure and life-styles and radical efficiency improvements in energy use.

The relative increases of energy use are shown more clearly in Table 8.2 where average annual growth rates are presented. Also the growth rates of the Global Low scenario are given for comparison. Thus the future energy use levels represent a radical change of the historical trends. This is more striking when we recall that the same GDP growth rates (see Table 3.13) were assumed for both solar scenarios and that they exceed the energy growth rates even of the Hard Solar scenario. A convenient way of specifying the degree of dependence between economic growth and energy growth at this aggregate level is by means of the energy-GDP elasticities, which are given in Table 8.3. A value of unity implies that economic growth and energy growth are closely coupled. This is evident for the historical elasticities. Especially on the global level the primary energy use and economic growth went hand in hand. But also in the Global Low scenario the elasticities decrease. In the solar scenarios even stronger decoupling of energy use and economic growth is achieved. The elasticities continuously decrease. The values of below 0.5 are typical and mean that if GDP should grow four-fold, energy use would less than double. The negative value encountered in the Soft Solar scenario means that energy use is decreasing during a period of economic growth. This is of course due to very strong energy conservation measures of the scenario. It should be noted here that the energy elasticities are the *results* of scenarios and not assumptions. Thus, the fact that the elasticities do not continuously decrease throughout the study period indicates that strong energy conservation and efficiency improvement measures are periodically offset by the need to introduce new energy

Table 8.2. Historical and Scenario Energy Growth Rates (%/yr)

	Historical	Scenario				
Energy Form	1950–1975	1975–2000	2000–2030	2030–2060	2060–2100	1975–2100[a]
Primary						
Hard Solar	3.8	1.6	1.1	1.1	0.6	1.1
Soft Solar	3.8	0.7	0.8	0.5	0.3	0.6
Region III[b]	5.0	1.6	1.0			
World[b]	5.1	2.0	1.7			
Final						
Hard Solar	3.6	1.0	0.6	0.6	0.6	0.7
Soft Solar	3.6	0.2	-0.3	0.3	0.2	0.1
Region III[b]	4.3	1.7	0.7			
World[b]	4.3	2.1	1.4			

[a] Average annual growth rates for the whole study period.

[b] Global Low scenario.

Table 8.3. Historical and Scenario Energy-GDP Elasticities

	Historical	Scenario				
	1950- 1975	1975- 2000	2000- 2030	2030- 2060	2060- 2100	1975-[a] 2100
Primary						
Hard Solar	0.83	0.71	0.75	0.62	0.54	0.66
Soft Solar	0.83	0.33	0.56	0.28	0.30	0.36
Region III[b]	0.96	0.65	0.73			
World[b]	0.99	0.67	0.93			
Final						
Hard Solar	0.79	0.43	0.40	0.36	0.52	0.43
Soft Solar	0.79	0.10	-0.18	0.15	0.19	0.08
Region III[b]	0.84	0.65	0.56			
World[b]	0.87	0.69	0.77			

a) Energy-GDP elasticities for the whole study period.

b) Global Low scenario.

sources (primary energy) and new energy forms (final energy) in order to achieve the transition to a sustainable energy future.

The extent of energy efficiency improvement embodied in the two scenarios can be seen in Figure 8.2 where final energy per unit of GDP is plotted against GDP per capita for the Hard and Soft Solar scenarios and the Global Low scenario for Region III. It can be seen that the ratio of final energy to GDP continues to decrease while the GDP per capita increases. The energy use efficiency improvements are very great in both Solar scenarios, and greatest in the Soft scenario. After 2030, with a continuous phase-out of conventional energy forms and increasing incorporation of hydrogen and other final energy forms converted from renewable energy, the efficiency improvements reach asymptotic values while GDP per capita continues to grow. The decrease of energy-GDP ratio is in line with the historical trends in developed parts of the world. In terms of energy-GDP elasticities this implies values less than unity. In fact the primary energy-GDP ratio has been decreasing in the U.S.A. ever since the 1900s at an average rate of one percent per year. In the Soft Solar scenario we encounter the same average annual decrease of this ratio (one percent per year), while in the Hard Solar it is about one half of a percent per year. On the other hand, we have already seen in Chapter 2 that this ratio has been increasing for the developing parts of the world, and that the Global Study indicates that it would continue to increase in these regions at least initially and that it would later flatten off and even start decreasing for Regions IV and VI (see Figure 2.4). All this points to the fact that Western Europe is entering a phase of post-industrial development in the two solar scenarios. The whole economy, energy system and energy use undergo a phase of infrastructural change after a phase of industrialization and economic development that has been completed in the past. This new development is underscored by the aggressive conservation measures in addition to the structural change of the energy system assumed in the scenarios. They reflect the belief that vigorous actions to increase energy efficiency and to improve energy productivity are necessities. Without such improvements the energy supply would surely prove to be inadequate and would not lead to use of sustainable energy potentials.

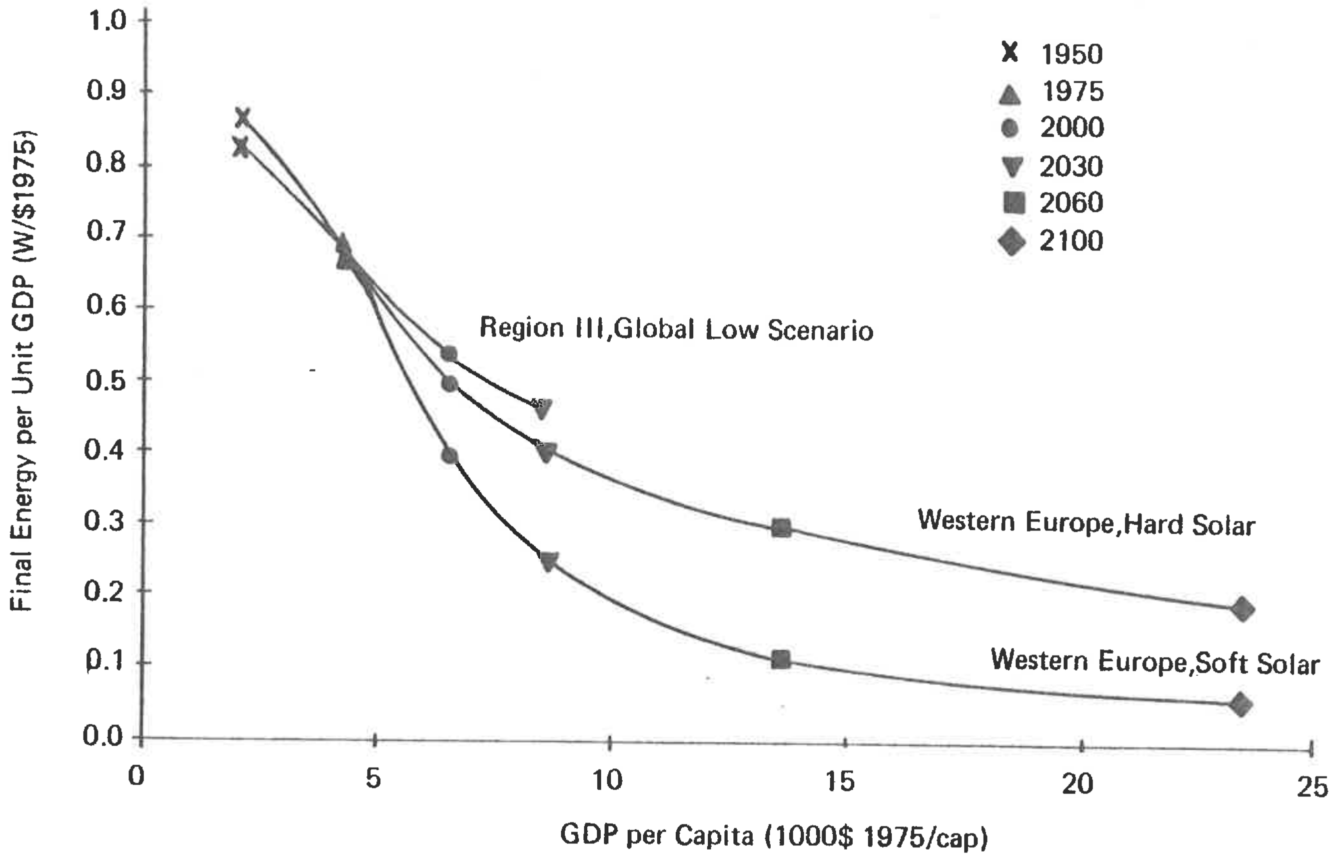

Figure 8.2. Energy intensiveness in the scenarios

Primary Energy Requirements

The bottom line of any energy accounting is the primary energy use. As a point of departure we will first describe the evolution of primary energy requirements by energy source in the two scenarios, keeping in mind the structure of the energy systems described in the previous chapter. Figures 8.3a and 8.3b show the relative shares of different primary energy sources. In Tables 8.4 and 8.5 the same shares and total primary energy from Figures 8.2 and 8.3 are also given. The first thing to observe is a gradual shift away from depletable fossil resources to sustainable use of alternative energy sources. Thus the transition is achieved to the reference energy systems of the two scenarios of the previous chapter. The transition, however, is not immediate, in the year 2060 fossil and nuclear energy are still used in both scenarios. Actually their use increases in absolute and even relative shares during the transition period. By the year 2000 only the relative shares of oil are lower than they are today. By that time, in the Hard Solar scenario, the use of natural gas and coal is amost twice as high as it is today. Consumption of gas and coal exceeds today's levels in the year 2000 and 2030 for the Soft and Hard Solar scenarios, respectively.

The sustainable energy sources are introduced slowly during the first three decades of the next century. By 2030, in the Hard Solar scenario, the centralized solar energy sources (producing electricity and hydrogen) contribute 36 percent of all primary energy. By the time this transition is completed this share increases to 86 percent. This high share of solar-thermal energy that is generated exclusively in the three high solar insolation zones of South Europe (see Figure 6.1 and Table 6.10) means that virtually all primary energy would originate from South Europe and abroad (see next section). The other 14 percent of total primary energy is shared by biomass and hydropower.

In the Soft Solar scenario the situation is more complex. We have already seen from the structure of the soft solar reference system that many different energy sources of local character must be utilized in addition to some use of centralized renewable sources in order to fulfill the energy supply requirements.

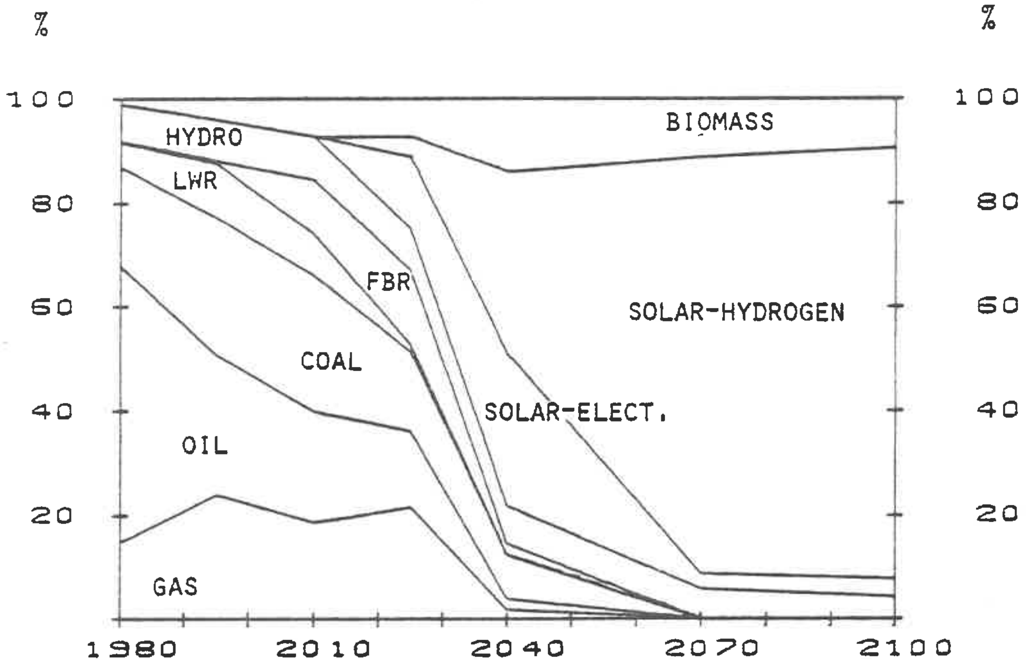

Figure 8.3a. Primary energy shares, Hard Solar scenario.

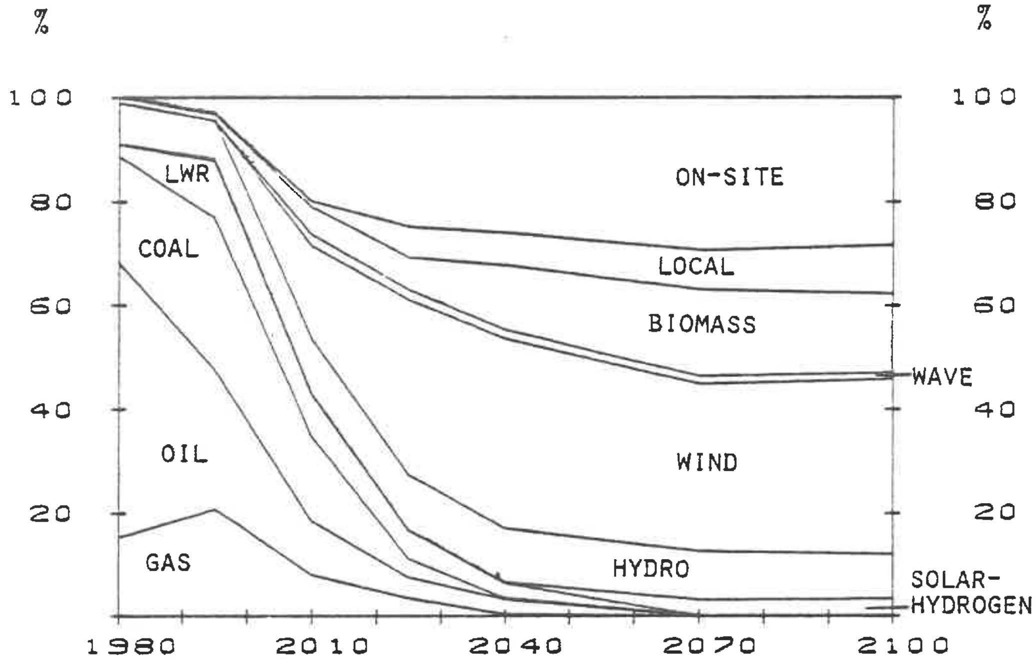

Figure 8.3b. Primary energy shares, Soft Solar scenario.

Table 8.4. Primary Energy (Equivalent) Shares, Hard Solar Scenario, 1975 to 2100 (%)

	Base Year	Scenario			
Energy Source	1975	2000	2030	2060	2100
Coal	22.1	26.3	12.6	2.4	0
Oil	52.5	24.7	9.5	0.6	0
Gas	13.2	21.9	13.7	0.5	0
LWR	2.4	9.5	0.8	0	0
FBR	0	4.1	9.5	0.6	0
(Nuclear Total)	(2.4)	(13.6)	(10.3)	(0.6)	(0)
Hydropower	8.1	8.1	7.7	6.2	4.3
Biomass	1.7	5.4	10.1	12.1	9.4
Solar-Electric	0	0	19.9	10.3	3.4
Solar-Hydrogen	0	0	16.2	67.3	82.9
(Solar Total)	(0)	(0)	(36.1)	(77.6)	(86.3)
Total (TWyr/yr)	1.53	2.29	3.20	4.47	5.76

Table 8.5. Primary Energy (Equivalent) Shares, Soft Solar Scenario, 1975 to 2100 (%)

	Base Year	Scenario			
Energy Source	1975	2000	2030	2060	2100
Coal	22.1	24.5	2.4	0.1	0
Oil	52.5	21.0	3.6	0.9	0
Gas	13.2	16.2	2.3	0.1	0
LWR	2.4	10.0	4.6	0.9	0
FRB	0	0.3	0	0	0
(Nuclear Total)	(2.4)	(10.3)	(4.6)	(0.9)	(0)
Hydropower	8.1	8.5	10.6	9.6	8.5
Windpower	0	6.3	34.8	33.6	33.9
Wavepower	0	0.8	1.8	1.5	1.4
Biomass	1.7	2.6	8.4	15.4	15.1
Solar-Hydrogen	0	0	0.1	2.3	3.4
Photovoltaics	0	0.7	6.0	7.2	9.4
On-Site Sources	0	9.1	25.4	28.4	28.3
Total (TWyr/yr)	1.53	1.84	2.36	2.75	3.16

By the year 2000 the collective contribution of these technologies is already significant. It is achieved by adding up a number of smaller sources and user-oriented energy technologies. This means that it would be necessary to pursue not one, but a host of separate research, development, commercialization, and marketing activities, different in both scope and character. These technologies should not only be accepted but should find a wide-spread active use and support by the consumer himself. In the scenario this was possible only by the explicit cost reduction of the user-oriented technologies with respect to the centralized (utility operated) ones. This cost bonus, presumably resulting from subsidies transferred from additional taxes levied on conventional sources, ranges between 40 and 60 percent (see Table 7.9). Thus, here we encounter a departure from cost minimal supply of energy that necessarily implies a wide spectrum of policy measures in the Soft Solar scenario.

Among the group of user-oriented technologies, on-site energy generation takes a central role. By the time the transition is completed to the sustainable reference system, on-site sources and wind power contribute over 60 percent of the primary energy supply. Together with biomass this share increases to 77 percent of the total energy supply.

Table 8.6 shows the shares of primary energy for the three parts of Western Europe in the Soft Solar scenario. Due to the extensive use of windpower, biomass and on-site energy sources, the primary energy in each part of Western Europe is proportional to the respective potentials of these renewable energy sources (see Chapter 6). In the Soft Solar scenario there is also a strong shift toward South Europe which would provide more than one half of all primary energy by 2100. This situation, however, is not so drastic as in the Hard Solar scenario, where eventually almost all primary energy originates from South Europe.

The evolution of primary energy shares shows that although it was possible to replace all of the consumptive use of depletable resources by renewable potentials, each scenario resulted in a gradual dependence on two to three energy sources. This situation is somewhat similar to the current dependence on

Table 8.6. Primary Energy (Equivalent), Soft Solar Scenario[a], 1975 to 2100 (%)

Europe	Base Year 1975	Scenario 2000	2030	2060	2100
North	9.8	9.2	8.5	8.5	8.5
Central	52.8	45.6	41.1	40.5	38.3
South	37.4	45.2	50.4	51.0	53.2
Western (TWyr/yr)	1.53	1.84	2.36	2.75	3.16

a) In the Hard Solar scenario most of the energy comes from solar conversion plants installed in South Europe, so that by 2100 almost 90 percent of primary energy originates from South Europe.

coal, oil and natural gas, and immediately poses the question of import dependence. The increasing import dependence and environmental degradation due to fossil energy consumption are perhaps the two most important reasons behind any attempt to increase the use of renewable energy sources. Table 8.7 shows the total primary energy consumption by source over the time horizon of the study together with the total endogenous availability of energy sources assessed in Chapter 6 (see Table 6.14). In both scenarios all domestic fossil sources are exhausted except coal. In the Hard Solar scenario the sustainable sources are used to the limit toward the end of the next century. The user-oriented energy sources are not utilized in this scenario. This is due to the lack of cost subsidies that are imposed in the Soft Solar scenario. In the Soft Solar scenario, on the other hand, these resources are still not used to their absolute limits in spite of the subsidies. This explains the need to import oil and natural gas during the transition period, although to a lesser extent than in the Hard Solar scenario. In any case, the fossil energy imports are eliminated in both scenarios before the year 2100.

It should also be noted that although the utilization of nuclear energy is larger in the Hard Solar scenario, it is import independent, whereas in the Soft Solar scenario natural uranium imports are necessary due to the low utilization of FBRs in this

Table 8.7. Cumulative Use of Primary Energy (Equivalent), Hard and Soft Solar Scenario, 1975 to 2100 (TWyr)

		Scenario			
		Hard Solar		Soft Solar	
Primary Energy Source	Total Resources Available[a]	Total Consumed	Remaining Resource or Total Imports[b]	Total Consumed	Remaining Resource or Total Imports[b]
Coal	370.9	40.2	330.7	19.1	351.8
Oil	15.8	39.4	- 23.6	27.1	- 8.3
Gas	9.2	30.2	- 21.2	13.1	- 3.9
LWR[c]	8.5	8.5	0	10.0	- 1.5
FBR[d]	1307.5	12.7	n.a.	0.2	n.a.
Hydropower	35.3	35.2	0.1	34.5	0.8
Wind/Wave Power	131.9	-	-	109.6	22.3
Photovoltaics	194.0	-	-	11.6	182.4
Biomass	56.3	56.3	0	42.3	14.0
Solar-Electric	49.3	49.3	0	-	-
Solar-Hydrogen	57.2	299.8	-242.67	6.1	51.1
On-Site	102.8	-	-	98.2	4.6

a) For fossil energy and LWR the total available resources represent the ultimately recoverable resources. For other renewable energy sources the numbers represent renewable potentials cumulated over 100 years (for hydropower over 120 years), as they become available (see Chapter 6 and in particular the resource summary in Table 6.14).

b) Total (cumulative) imports are represented by negative numbers.

c) The LWR cumulative fuel consumption in the Hard Solar scenario would also exceed the natural uranium resource, but after the exhaustion of the domestic natural uranium the advanced LWRs are used and fueled by U^{233} produced in the FBR.

d) FBR potential is based on depleted natural uranium resource of Western Europe; the potential could be even higher, but we only use the depleted uranium stockpile left over from LWR, resulting in the given estimate of this energy source. Thus the remaining resource estimate is not applicable (n.a.). In the Hard Solar scenario, FBRs also breed U^{233} in addition to plutonium. U^{233} is converted from thorium. Thorium is assumed to be available to the extent that it is needed.

scenario. In the Hard Solar scenario there are enough FBRs to breed fissile material after reprocessing to meet the fuel requirements of LWRs which exceed domestic uranium resources. In the Soft Solar scenario this is not the case since less than 3 GW(e) installed capacity of FBR are utilized (roughly two power plants of the Super-Phenix type).

Especially striking are the large import requirements of the solar thermolytic hydrogen in the Hard Solar scenario. The endogenous solar thermal potential (of South Europe) is practically exhausted by electricity production, so that most of the required hydrogen is imported.

Table 8.8 shows the import dependence as a fraction of total primary energy requirements for the two scenarios. In the Soft Solar scenario a gradual decrease of import dependence is achieved, resulting in complete reliance on domestic renewable sources by 2100. Even in the Hard Solar scenario the import dependence is lower in 2030 than today. In terms of oil requirements alone the reduction is especially dramatic. In the year 2030 about 88 GWyr/yr of oil must be imported by Western Europe in the Hard Solar scenario and only 33 GWyr/yr in the Soft Solar scenario. Recalling the oil trading between the world regions of the Global Low scenario given in Figure 2.7 (see Chapter 2), this represents only 5.5 and 2.1 percent of the 1600 GWyr/yr of the oil imported by Region III, an amount that should be readily available to Western Europe.

Unfortunately, as time progresses the energy import dependence increases again in the Hard Solar scenario mainly due to the large hydrogen import requirements mentioned above. This raises the question of whether such large amounts of hydrogen would be actually available on the world market.

Hydrogen Imports

In Chapter 6 we have argued that most of the centralized solar thermal electric conversion plants (STEC) would be located within the three high insolation zones of South Europe (see Figure 6.1 and Table 6.10). Due to the fact that the solar thermal potential of these zones is partially devoted to electricity generation by the year 2100 in the Hard Solar

Table 8.8. Primary Energy Import Dependence, Hard and Soft Solar Scenario, 1975 to 2100 (%)[a]

	Base	Scenario							
	Year	Hard Solar				Soft Solar			
Primary Energy Resource	1975	2000	2030	2060	2100	2000	2030	2060	2100
Coal	11	0	0	0	-	6.6	0	0	0
Oil	95	49.4	29.0	100.0	-	38.6	10.2	0	0
Gas	8	52.6	100.0	100.0	-	37.4	73.9	100.0	0
Nuclear	0	0	0	0	0	50.0	100.0	100.0	0
Hydro	0	0	0	0	0	0	0	0	0
Biomass	0	0	0	0	0	0	0	0	0
Renewable-Electric	-	-	-	-	-	0	0	0	0
Solar-Electric	-	-	0	0	0	-	-	-	-
Solar-Hydrogen	-	-	88.5	87.3	81.7	0	0	0	0
On-Site	-	-	-	-	-	0	0	0	0
Total	53	23.7	30.8	59.8	67.8	15.8	2.1	0.1	0

---

a) Energy import dependence is calculated as a fraction of imported energy in total use of a given energy source. The total import dependence represents a fraction of total imported energy in total domestic energy use of all sources.

scenario, only about 18 percent of the required hydrogen can be produced in Western Europe. The other 82 percent have to be imported. This amounts to about 3.9 TWyr/yr of (primary equivalent) hydrogen import requirements.

An important feature of the hard solar reference system is that all electricity and hydrogen produced in South Europe is transported to consumption centers by long-distance electricity transmission links and hydrogen pipelines. Thus we have not assumed any hydrogen transportation in liquefied form. Due to the long time horizon it is conceivable that intercontinental transportation of liquefied hydrogen by large tankers would become attractive. However, cryotransport on such a scale is two times greater than the total amount of crude oil transported from North Africa and the Middle East today (about 1.6 TWyr/yr in 1975). The technology is neither easy nor inexpensive. If it becomes available hydrogen could be imported to Western Europe from wherever it should be available.

A second more practical possibility would be the expansion of the Western European hydrogen pipeline links. Possible extensions beyond the Western European borders are to the Middle East and North Africa. Such an extended hydrogen pipeline transport system would make the vast areas of the Sahara available for hydrogen production. Here the land potential for solar thermal power plants would not be a constraint. The total land area of the Sahara is about 9.1 million square kilometers, or about twice the size of Western Europe (see Table 3.2). This area is very sparsely populated, and almost 90 percent is covered by deserts. Considering the very high mean solar insolation and almost negligible cloud cover throughout the year, less than one percent of the desert area would be required for the production of hydrogen required by Western Europe. Certainly it would not be a problem to use one percent of this area for energy production by carefully choosing sites where the movement among the sand dunes has ceased or by using rocky plateaus (hammada) for the construction of solar power plants. Due to the lack of water in such desert areas, transmission of electricity to the Mediterranean Sea would be required instead of in-situ hydrogen thermolysis. On the sea coast electrolytic hydrogen could be produced and then transported by pipeline to Western Europe. In-situ hydrogen production is also conceivable if a secondary pipeline grid were used to provide water for hydrogen thermolysis. This is perhaps an unrealistic scheme, but it offers a vast source of hydrogen potentially available to Western Europe. 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.

A third possibility is simply to import fossil sources to Western Europe instead of hydrogen. Today approximately 0.5 TWyr/yr of natural gas are flared world-wide. In addition, the natural gas resources are large so that a pipeline system to Western Europe could be used to import up to 3.9 TWyr/yr of natural gas from North Africa and the Middle East and elsewhere in the world, at the same costs assumed for hydrogen in the scenario. However, this would mean that the Hard Solar scenario would cease to be based on sustainable sources of energy.

We have seen that the gradual transition to sustainable sources of energy in the scenarios required on the order of 100 years and that it was necessary to exploit fossil and nuclear energy during the transition at higher levels than today. The transition was not achievable in a shorter period of time, and had it lasted longer, larger amounts of depletable energy would have been necessary. Thus, time is also one of the important resources required in the scenarios.

Translated into more intuitive terms, the time constraint means that new facilities can be built at rates not exceeding a certain maximum (specified in Table 7.8). It also means that the construction and structural changes must occur gradually so that the whole energy system is always in balance. For example, electricity generation plants cannot be built over night; they must be ordered, constructed and licenced, and the supporting infrastructure such as electricity grids must also be installed. On the other hand, to build these facilities in anticipation of possible demand in the long-term future would be uneconomic and therefore unrealistic. The minimum cost criterion under constraints assures that such things do not occur. The balance in the whole energy system is always assured.

Secondary Energy

The next level of the energy system at which we analyze this balance are the secondary energy forms that result from conversion of primary energy. Recalling the schematic representation of the energy system from Figures 7.3 and 7.4, the secondary energy forms result in final energy delivered to the user after transportation and distribution. The most important forms of secondary energy in the scenarios are gaseous and liquid fuels and electricity.

Figures 8.4 and 8.5 give the evolution of gaseous fuel supply in the two Solar scenarios. Here we observe a continuous transition from natural gas to hydrogen supply. Natural gas is imported to meet the demand in excess of domestic resources. It requires no conversion facilities so that it represents at the same time a primary and a secondary energy form. Hydrogen, on the other hand, is converted either from electricity or directly in the solar thermal plants, most of it originating from North Africa as was explained above. Table 8.9 gives the required capacities of hydrogen conversion plants, both electrolytic and thermolytic (including those in North Africa). The installed capacities are almost ten times higher in the Hard Solar than in the Soft Solar scenario. Here we already see some drastic differences between the two scenarios with respect to the evolution of the energy system. After 2030 the build-up rates of hydrogen conversion facilities are very large in the Hard Solar scenario and if not followed consequently they are probably not achievable. Such large capacities are required, since in this scenario hydrogen serves for generation of electricity, high (furnace) to low temperature heat, and transportation purposes. In the Soft Solar scenario the demands are much lower and in addition almost all low temperature heat is generated on-site (roof collectors, etc.).

Currently the largest electrolysis plant (Norsk-Hydro in Norway) has a capacity of 200 MW and with future increases in power density, plants on the order of 1 GW capacity are certainly in sight for the next century. This would translate into about

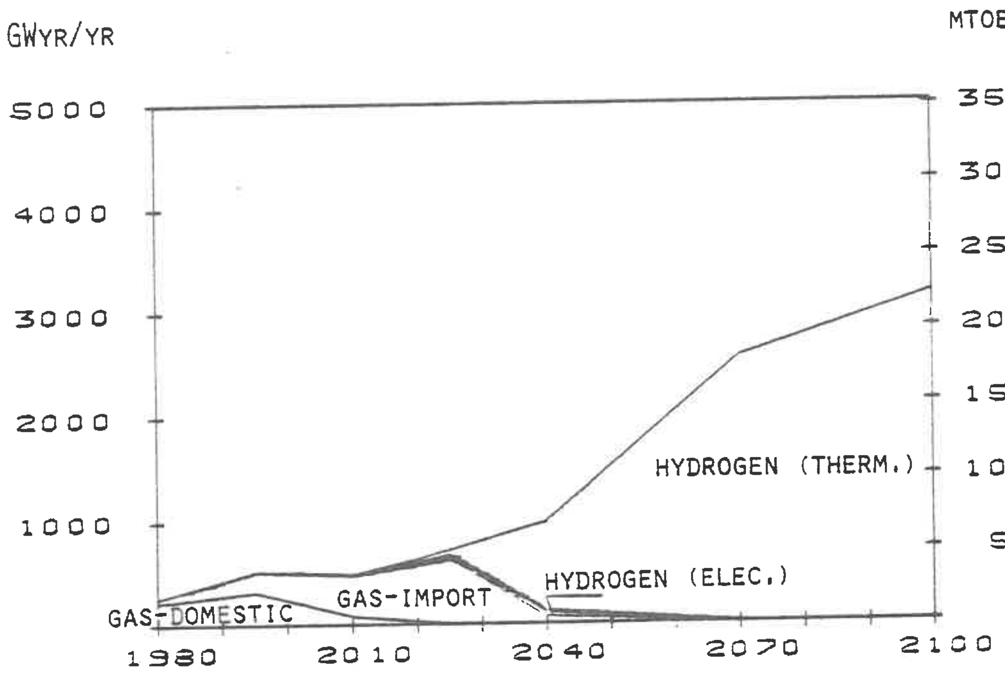

Figure 8.4. Secondary gaseous fuels, Hard Solar scenario.

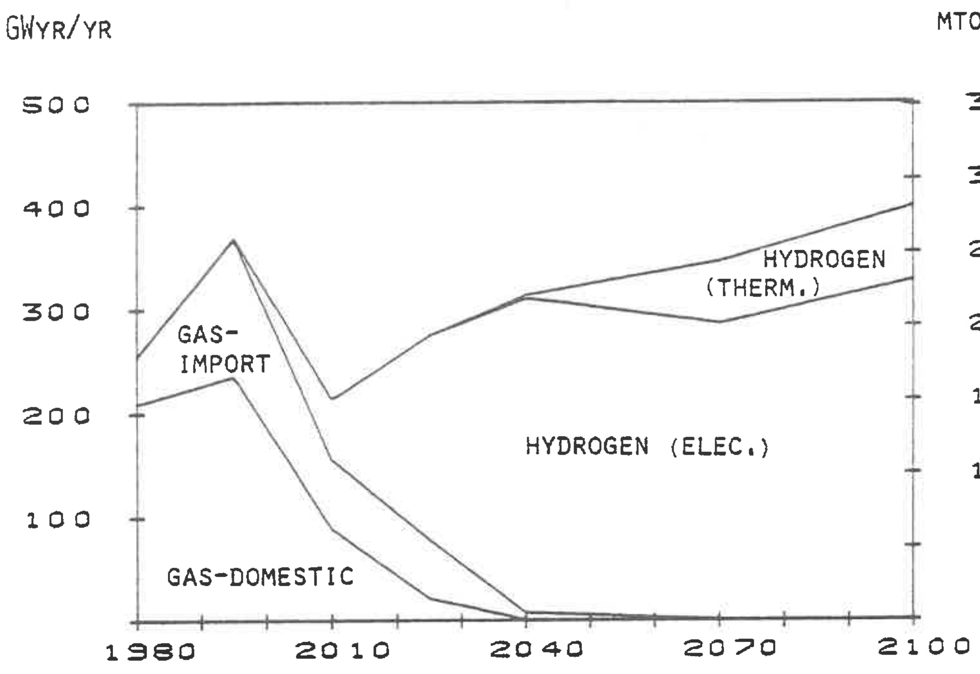

Figure 8.5. Secondary gaseous fuels, Soft Solar scenario.

Table 8.9. Installed Capacities[a] for Hydrogen Production, Hard and Soft Solar Scenarios (GW)

Hydrogen Conversion Plants	Scenario Hard Solar 2000	 2030	 2060	 2100	 Soft Solar 2000	 2030	 2060	 2100
Solar-Thermal								
Electrolysis	0	77.3	15.5	0	–	–	–	–
Thermolysis[b]	0	798.4	4984.4	7918.9	0	3.1	103.9	177.7
Other								
Electrolysis	4.8	116.9	77.5	0	52.4	435.6	536.9	658.6
Total	4.8	992.6	5077.4	7918.9	52.4	438.7	640.8	836.3

[a] The installed capacities in the reference year 1975 are negligible.

[b] 82 percent originates from North Africa and the Middle East in 2100, see Table 8.8.

eight thousand installations in the Hard Solar scenario and about 800 in the Soft Solar.

Electricity generation is closely coupled with hydrogen production in the scenarios, since some of the hydrogen is converted into electricity in fuel cells. The main reason for this double conversion is the electricity storage problem.

Currently 65 percent of all electricity is generated by fossil power plants (see Table 3.5). Fossil fuels are easy to store due to relatively high energy densities, so that electricity generation can follow very closely the electricity demand loads. As electricity generation is slowly shifted to renewable energy sources such as wind and solar insolation, the load following generation mode is not possible any more. This means that electricity would have to be stored. This is also foreseen in the scenarios. Pumped hydro storage is used to balance daily load variations. However, for seasonal variations the storage capacity requirements would be too excessive. Thus an alternative approach was chosen, namely to store hydrogen and convert it into electricity when the demand is high.

Table 8.10 shows the production, storage and actual deliveries of hydrogen (after storage). By 2100 about 19 percent of all hydrogen is delivered through storage in the Hard Solar and about 14 percent in the Soft Solar scenario. Due to the much lower hydrogen production levels the storage capacities of the Soft Solar scenario are accordingly lower than in the Hard scenario. Thus, in this way it is possible to balance the seasonal electricity supply through hydrogen storage and electricity conversion in fuel cells.

Figure 8.6 and 8.7 show the electricity generation by energy source for the two scenarios. It should be observed that the amounts of generated electricity by the year 2100 are practically the same in both scenarios: 878 GW(e)yr/yr in the Hard Solar and 826 GW(e)yr/yr in the Soft Solar scenario. However, the sources of electricity are different. In the Hard Solar scenario about 57 percent of generated electricity comes from hydrogen conversion in fuel cells, the remainder is almost evenly divided between hydropower and solar thermal power plants. In the Soft Solar scenario only 8 percent of all electricity is generated

Table 8.10. Hydrogen Production, Storage and Delivery (GWyr/yr)

	Scenario							
	Hard Solar				Soft Solar			
Hydrogen	2000	2030	2060	2100	2000	2030	2060	2100
Production								
Electrolysis	2.5	26.6	13.6	0	19.9	232.3	291.5	328.6
Thermolysis	0	313.5	1957.5	3109.9	0	1.3	41.3	70.2
Storage								
Input	-0.6	-118.5	-431.8	-604.9	-4.8	-24.4	-45.3	-57.5
Output	0.6	112.6	410.2	574.7	4.6	23.2	43.0	54.6
Delivery	2.5	334.2	1949.5	3079.7	19.7	232.4	330.6	395.9
Share Delivered Through Storage (%)	23.7	33.7	21.0	18.7	23.4	10.0	13.0	13.8
Storage Capacity (GW)[a]	2.3	231.1	842.0	1179.6	14.5	63.4	125.8	150.2

a) Numbers refer to throughput capacity and not total storage "volume".

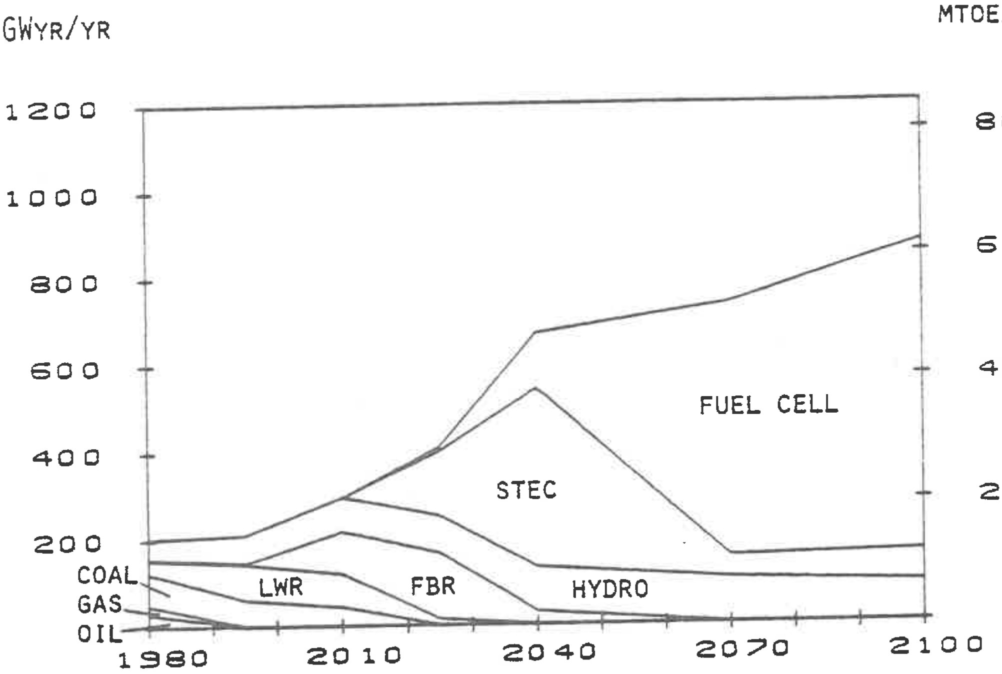

Figure 8.6. Electricity generation, Hard Solar scenario.

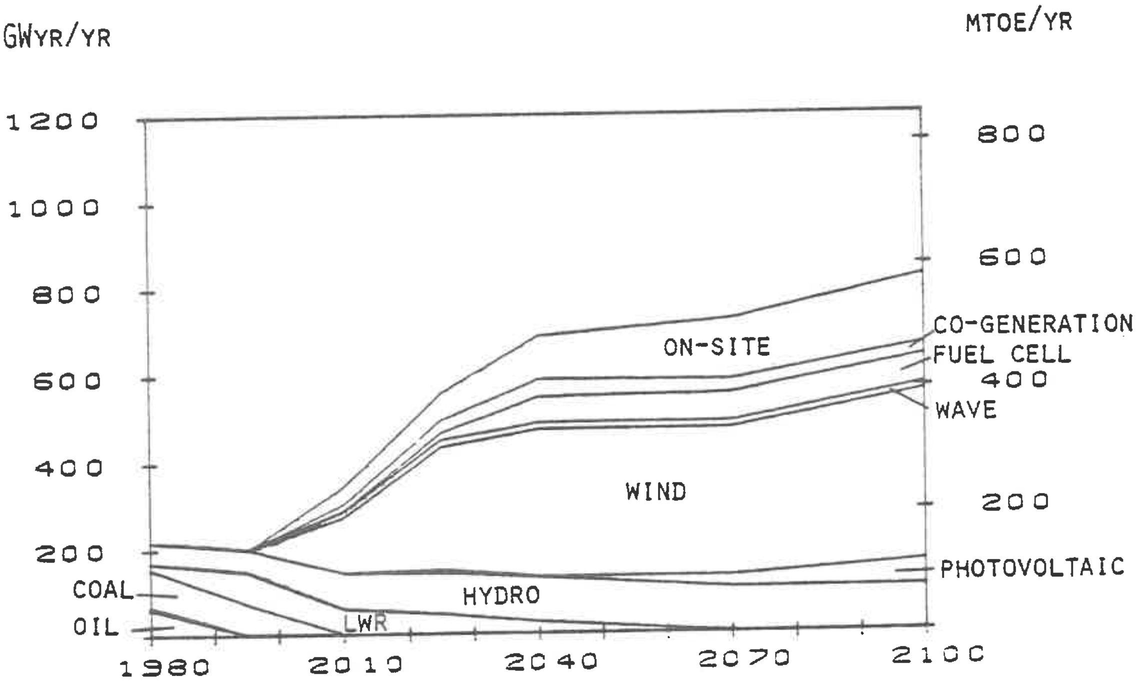

Figure 8.7. Electricity generation, Soft Solar scenario.

from hydrogen. Here wind power contributes the largest share--48 percent of all electricity generation. Utility operated photovoltaic plants contribute another 7 percent and hydropower 13 percent. On-site (user-operated) electricity generation systems take a special role in this scenario with a 19 percent share in total generation. Altogether, one fifth of electricity is generated on site, largely by photovoltaic arrays on the roof and south wall of the houses and small wind and biomass plants. Finally a small amount of biomass is used for co-generation of electricity and district heat, contributing 3.5 percent of the total electricity generation. In this scenario fuel cells are also used in a co-generation mode--all waste heat is utilized for district heat. Thus, not only are the sources of electricity different in the two scenarios, but also to the extent that they are the same, they are used under a different regime. This is reflected in the structure of the installed capacities of electric power plants in Table 8.11 and 8.12. It is really striking that the installed capacities are twice as large in the Soft Solar scenario, although the generated electricity is almost the same in both scenarios. This of course is the consequence of the relatively low capacity utilization in the Soft Solar scenario. In the Hard Solar scenario fuel cells operate at 77 percent of installed capacity and solar thermal plants at 69 percent resulting in an average installed capacity utilization of 71 percent. This is possible due to the extensive use of hydrogen as a storage medium. In the Soft Solar scenario, on the other hand, the total average installed capacity utilization is only 31 percent. Photovoltaics have the lowest plant factors of only 12 percent. On-site systems are utilized at 28 percent and wind power at 36 percent of rated capacity. This is all connected with the lack of extensive use of hydrogen for electricity storage described above. Instead, all capacities have to be large enough to meet most of the demand peaks. This is especially true for all on-site and photovoltaic systems, and also for the small amounts of hydrogen that are used. In the Hard Solar scenario high utilization of fuel cells is possible since they generate electricity the whole time, in the Soft Solar scenario they are used in a co-generation mode and are therefore

Table 8.11. Installed Capacities for Electricity Generation, Hard Solar Scenario (GW(e))

Electricity Conversion Plant	Base Year 1975	Scenario 2000	2030	2060	2100
Fossil Thermal	248.7	382.5	145.7	0	0
Nuclear	18.1	153.8	162.0	13.5	0
Hydropower	113.4	153.2	201.8	228.8	204.0
Solar Thermal	0	0	340.0	246.0	104.6
Fuel Cells	0	0	222.8	696.4	926.0
Total	380.2	689.6	1072.3	1184.7	1234.6

Table 8.12. Installed Capacities for Electricity Generation, Soft Solar Scenario (GW(e))

Electricity Conversion Plant	Base Year 1975	Scenario 2000	2030	2060	2100
Fossil Thermal	248.7	185.0	0	0	0
Nuclear	18.1	93.3	53.5	12.2	0
Hydropower	113.4	140.2	217.9	231.2	232.7
Photovoltaics	0	0	31.8	212.6	505.8
Windpower	0	127.7	845.8	951.1	1102.8
Wave Power	0	9.6	28.9	28.0	28.9
Fuel Cell	0	1.2	41.5	140.8	148.9
Co-Generation	0	8.1	85.7	89.6	79.5
On-Site[a]	0	39.0	189.2	401.9	549.8
Total	380.2	604.1	1494.3	2068.3	2648.4

[a] On-site electricity conversion facilities are user operated. The electricity grid connection serves only for utilization of excess capacity.

utilized only during the cold seasons when the district heat is also needed resulting in a relatively low utilization of about 44 percent.

The relatively low utilization of installed capacity in the Soft Solar scenario is also to a lesser extent due to the lack of daily (pumped hydro) electricity storage. Table 8.13 shows electricity generation, storage and delivery in the two scenarios. In the Hard Solar scenario daily storage of electricity is used (for day-night cycle) to allow much better plant factors for STEC

Table 8.13. Electricity Generation, Storage and Delivery (GW(e)yr/yr)

	Scenario							
	Hard Solar				Soft Solar[a]			
Electricity	2000	2030	2060	2100	2000	2030	2060	2100
Production								
Thermal (Fossil)	167.0	121.5	10.1	0	118.6	40.1	9.2	0
Hydropower	68.9	90.8	102.0	91.8	61.5	98.0	104.0	104.7
Solar Thermal	0	236.2	170.8	72.7				
Renewable/On-Site					66.5	433.4	537.7	656.6
Fuel Cell	0	49.2	431.2	713.9	0.3	30.7	63.2	65.1
Storage								
Input	0	-27.8	-20.1	0				
Output	0	9.5	6.0	0				
Delivery	238.9	490.0	712.4	878.3	217.9	246.9	602.3	826.4
Share Delivered Through Storage (%)	0	4.1	1.0	0				
Storage Capacity (GW(e))[b]	0	125.5	50.3	0				

a) Electricity storage was not used in the Soft Solar scenario, load following electricity generation turned out to be more economical.

b) Numbers refer to throughput capacity and not total storage "volume".

plants. In the Soft Solar scenario load following electricity generation, especially of the on-site and local renewable sources, turned out to be more cost effective. In both scenarios, however, electricity is utilized mainly for such demand categories where specific heat cannot be used (e.g. air conditioning, lighting). This of course reduces to an extent the mismatch between the generation and the load profiles, eliminating most of the extreme peaks.

Today liquid fuels take a special role in the energy system--they are not easily substitutable by electricity or natural gas, since they are practically the only source of energy for free-range vehicles. In the scenarios they are slowly substituted by other forms of secondary energy and by 2100 their role is largely limited to non-energy uses, e.g. feedstocks. In addition, while most of the liquid fuels are converted from oil today, in the scenarios methanol is increasingly produced from biomass and hydrogen. Only during the transition period are small amounts of methanol produced from coal. Figures 8.8 and 8.9 show the liquid fuel supply for the two scenarios. In the Hard Solar scenario the liquid fuel supply is reduced by 40 percent in the year 2100 and in the Soft Solar scenario by 75 percent. This means that most of the traditional uses of liquids such as in transportation are replaced by gaseous fuels and electricity. In addition, by 2100 liquids are no longer used as a source of heat. Even the on-site solar heating systems rely on biomass or hydrogen as a back-up fuel.

Thus the secondary energy balances show a very strong shift away from solid and liquid fuels. Tables 8.14 and 8.15 show the resulting secondary energy balances for the two scenarios. In the Hard Solar scenario the shares of gaseous fuels and electricity increase and in the Soft scenario the shares of electricity and on-site energy sources grow while the shares of gaseous fuels decrease slightly. Within each category--the solid, liquid and gaseous fuels--there is a complete transition away from fossil toward renewable sources of energy. In the Soft Solar scenario, in addition, on-site local forms of energy also substitute other forms supplied centrally by utilities. By 2100 almost 40 percent of all secondary energy is produced

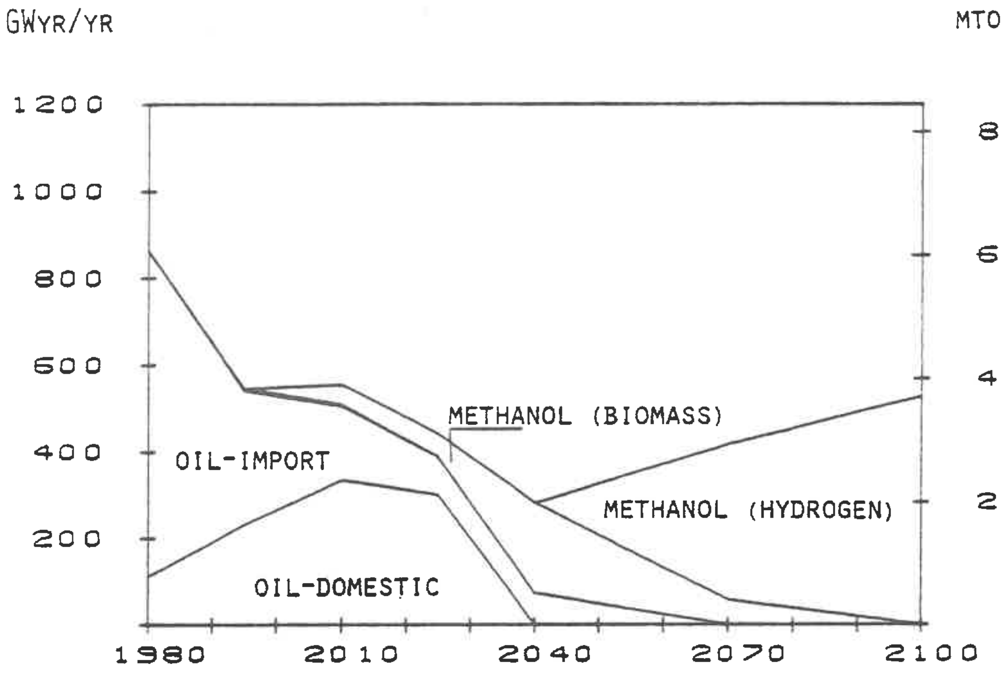

Figure 8.8. Secondary liquid fuels, Hard Solar scenario.

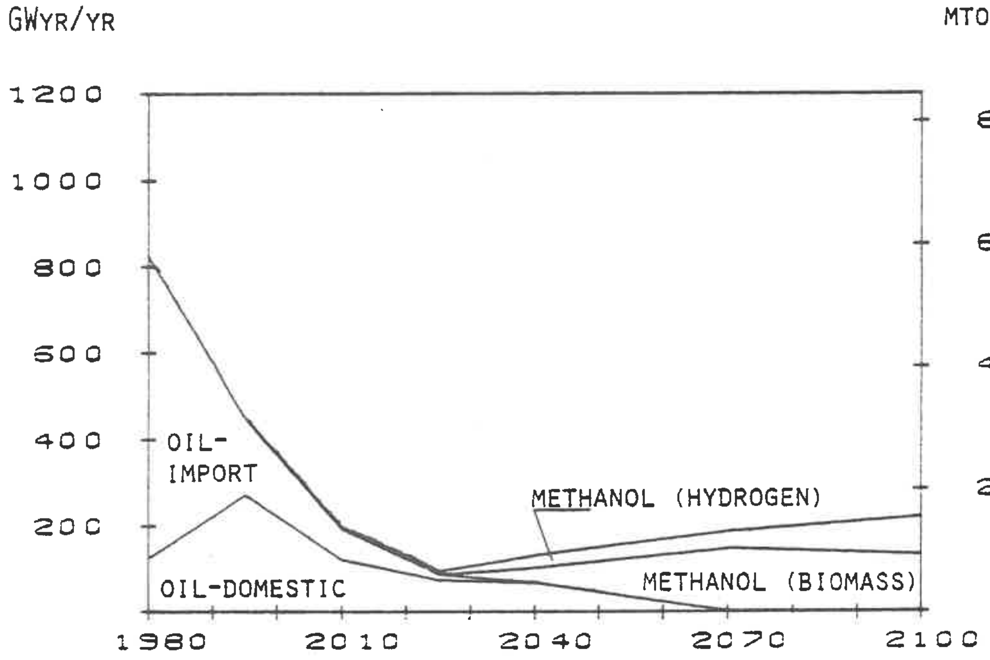

Figure 8.9. Secondary liquid fuels, Soft Solar scenario.

Table 8.14. Secondary Energy Shares by Form, Hard Solar Scenario, 1975 to 2100 (%)

Form	Base Year 1975	Scenario 2000	2030	2060	2100
Solid (total)	(11.7)	(14.7)	(19.0)	(9.1)	(3.0)
Coal	9.7	9.5	13.9	4.4	0.1
Biomass	2.0	5.2	5.1	4.7	2.9
Liquid (total)	(57.2)	(33.3)	(19.5)	(15.3)	(17.0)
Oil	57.2	32.0	14.2	1.0	0
Methanol	0	1.3	5.3	14.3	17.0
Gaseous (total)	(18.1)	(30.5)	(36.4)	(47.3)	(51.9)
Natural Gas	18.1	30.4	22.1	1.0	0
Hydrogen	0	0.1	14.3	46.3	51.9
Electricity	13.0	21.5	25.1	28.3	28.1
Total (TWyr/yr)	1.29	1.65	1.99	2.44	3.11

Table 8.15. Secondary Energy Shares by Form, Soft Solar Scenario, 1975 to 2100 (%)

Form	Base Year 1975	Scenario 2000	2030	2060	2100
Solid (total)	(11.7)	(22.7)	(14.2)	(10.7)	(8.0)
Coal	9.7	20.3	4.5	0.2	0.1
Biomass	2.0	2.4	9.7	10.5	7.9
Liquid (total)	(57.2)	(27.0)	(8.5)	(12.5)	(15.0)
Oil	57.2	26.6	6.3	1.6	0
Methanol	0	0.4	2.2	10.9	15.0
Gaseous (total)	(18.1)	(23.3)	(18.4)	(15.7)	(15.5)
Natural Gas	18.1	21.9	4.4	0.2	0
Hydrogen	0	1.4	14.0	15.5	15.5
Electricity	13.0	16.4	20.7	18.6	19.7
District Heat	0	0.7	2.8	2.9	2.3
On-Site	0	9.9	35.4	39.6	39.5
Total (TWyr/yr)	1.20	1.35	1.25	1.35	1.48

on site by the user himself. It should be noted that the comparison of the relative shares of on-site energy with other forms is not exact. All other energy forms are converted from primary energy sources into secondary forms in central, usually large, facilities. From there the energy has to be transported and distributed to final use causing losses, but in spite of these additional losses the centralized conversion is more efficient. On-site energy, on the other hand, needs negligible transportation and distribution, it is generated and used locally, thus transportation and distribution losses are small. Because of the local character of on-site energy forms, the difference between secondary and final energy is minimal, while for the other centralized forms of energy this difference is a function of transportation and distributon efficiency. The final energy balance is also the last level of energy system before energy is put to actual use.

Final Energy

Figures 8.10a and 8.10b and Tables 8.16 and 8.17 show the final shares by form. Direct comparison with Tables 8.14 and 8.15 showing secondary energy shares indicates the transportation and distribution efficiencies at an aggregate level. In 1975 about 92 percent of all secondary energy was delivered as final, by 2100 the efficiency slightly decreases to 90 percent in the Hard Solar due to a larger share of long distance energy transport, but increases to 94 percent in the Soft Solar scenario because of the large share of on-site energy generation. Beyond such similar shifts in shares of various energy forms, the overall structure is equivalent to the secondary energy shares. However, we have already observed the strong substitution within each category of secondary energy forms; this is of course translated directly in strong shifts in the kind of final energy delivered to use (or what is equivalent to demand categories of Chapter 5).

From the point of energy use 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.

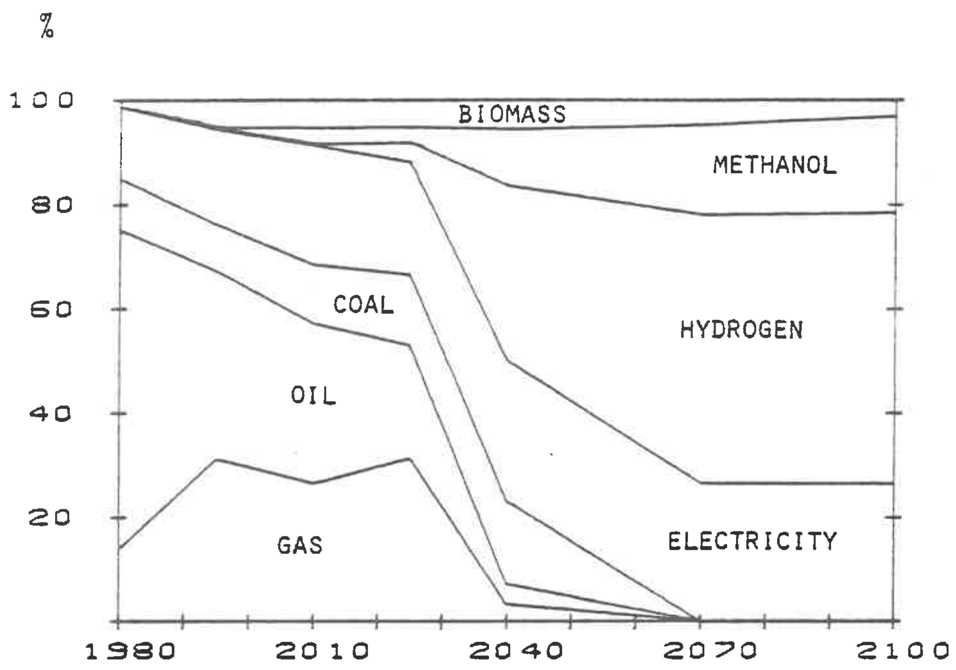

Figure 8.10a. Final energy shares by form, Hard Solar scenario.

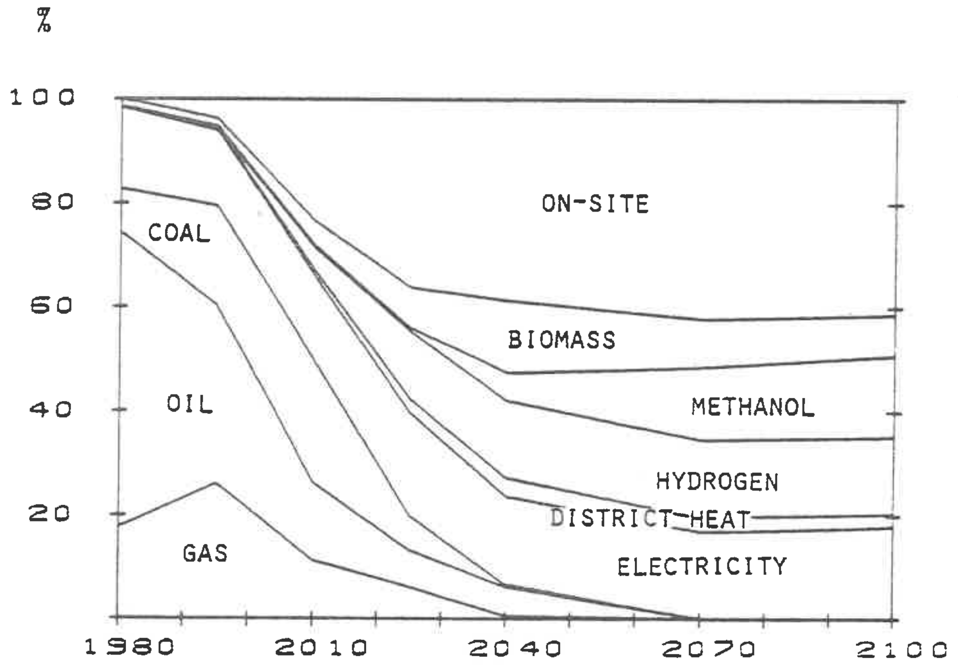

Figure 8.10b. Final energy shares by form, Soft Solar scenario.

Table 8.16. Final Energy Shares by Form, Hard Solar Scenario (Higher Demand Projection), 1975 to 2100 (%)

Form	Base Year 1975	Scenario			
		2000	2030	2060	2100
Coal	10.1	9.7	14.5	4.6	0.1
Oil	59.5	34.0	15.2	1.1	0
Gas	16.4	29.6	21.8	1.0	0
Electricity	11.8	19.9	23.4	26.6	26.5
Biomass	2.2[a]	5.4	5.3	4.9	3.1
Methanol	0	1.3	5.7	15.5	18.5
Hydrogen	0	0.1	14.1	46.3	51.8
Total (TWyr/yr)	1.19	1.52	1.82	2.20	2.81

Table 8.17. Final Energy Shares by Form, Soft Solar Scenario (Lower Demand Projection), 1975 to 2100 (%)

Form	Base Year 1975	Scenario			
		2000	2030	2060	2100
Coal	10.1	20.6	4.6	0.2	0.1
Oil	59.5	27.9	6.6	1.7	0
Gas	16.4	21.2	4.2	0.2	0
Electricity	11.8	15.0	18.9	16.8	17.8
Biomass	2.2[a]	2.5	9.8	10.6	7.9
Methanol	0	0.5	2.4	11.3	15.6
Hydrogen	0	1.4	13.5	14.8	14.9
District Heat	0	0.7	2.9	3.1	2.5
On-Site	0	10.3	37.1	41.2	41.2
Total (TWyr/yr)	1.19	1.26	1.17	1.27	1.39

a) Biomass use in 1975 refers mostly to fuel wood.

The actual use of final energy forms changes. For example oil refinery products have a very wide-spread use today--as a source of heat, as vehicle fuel and as feedstocks in the chemical industry (besides their primary energy use as a source of electricity). In the scenarios, methanol is the major liquid fuel, but its use is largely limited to feedstocks. As a source of heat, oil products are replaced by many other final energy forms (e.g. biomass, on-site generation, hydrogen, etc.), and as a fuel in transportation mainly by electricity and hydrogen.

Thus at the level of final energy the structural changes of the energy system must be analyzed at least according to energy form, energy use and the distribution between various sectors of the economy.

Table 8.18 shows the various forms of final energy use in 1975. It is worth noting that except for thermal (low and high temperature) uses each energy form supplies only one specific use and that each of the non-thermal uses is supplied by only one energy form. This illustrates the obvious, that fuel substitution is relatively easy only in thermal uses of energy. Table 8.19 shows the use of final energy forms for the Hard Solar scenario in 2100. Here the situation is different. First of all, as we already know, fossil energy forms have been fully substituted by biomass, methanol and hydrogen. But only hydrogen and biomass have thermal uses. In fact, hydrogen rather than methanol can be seen as the replacement for oil; it has the most wide-spread use in 2100. The diversification in fuel uses has increased somewhat by this time; in most use categories two energy forms are utlized. The increase in diversification is even greater in the Soft Solar scenario, shown for the year 2100 in Table 8.20. The thermal uses somehow resemble the current situation where many energy forms are utilized. In this scenario electricity and on-site energy together can be viewed as oil replacement. They are the most wide-spread energy forms.

Tables 8.21 and 8.22 show the evolution of final energy uses for the two scenarios. In the Hard Solar scenario thermal use of final energy and motor fuels decreases continuously from a 77 percent share to 57.5 percent between 1975 and 2100, while electricity use and feedstocks (non-energy use of final energy) more than double their share from 19 percent to 40 percent during the same period. Exactly the same trend can be observed in the Soft Solar scenario, except that here the decrease of thermal uses and the increase of electricity are more dramatic. Their joint share in all final energy uses, however, is about the same in both scenarios by 2100--65 percent in the Hard Solar and 68 percent in the Soft Solar scenario. It should be observed that in the Soft Solar scenario 41 percent of all final energy is delivered by on-site systems including 11 percent of specific electricity uses (see Table 8.17).

Table 8.18. Final Energy by Form and Use, Base Year 1975 (GWyr/yr)

Final Energy Form	Final Energy Use Thermal Low	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 8.19. Final Energy by Form and Use, Hard Solar Scenario, 2100 (GWyr/yr)

Final Energy Form	Final Energy Use Thermal Low	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

form, energy use and the distribution between various sectors of the economy.

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

Final Energy Form	Final Energy Use Thermal Low	 High	 Steel Pro-duction	 Feed-stocks	 Motor Fuels	 Elec-tricity	 Co-genera-tion	 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 8.21. Final Energy Shares By Use, Hard Solar Scenario, 1975 to 2100 (%)

	Base Year	Scenario			
Use	1975	2000	2030	2060	2100
Thermal Low	42	36.5	35.6	32.4	30.1
Thermal High	14	13.5	12.9	11.7	11.2
(Thermal Total)	(56)	(50.0)	(48.5)	(44.1)	(41.3)
Steel Production	4	4.0	3.4	2.4	2.2
Feedstocks	7	8.9	11.2	16.1	18.5
Motor Fuels	21	22.6	19.0	15.6	15.0
Electricity	12	14.5	17.9	21.8	23.0
Total (TWyr/yr)	1.19	1.52	1.82	2.20	2.81

Table 8.22. Final Energy Shares by Use, Soft Solar Scenario, 1975 to 2100 (%)

	Base Year	Scenario			
Use	1975	2000	2030	2060	2100
Thermal Low	42	37.0	41.4	37.8	33.9
Thermal High	14	12.2	10.4	9.8	8.9
(Thermal Total)	(56)	(49.2)	(51.8)	(47.6)	(42.8)
Steel Production	4	3.6	2.4	2.3	2.3
Feedstocks	7	8.2	10.5	13.2	15.6
Motor Fuels	21	22.0	14.9	13.8	14.0
Electricity	12	17.0	20.4	23.1	25.3
Total (TWyr/yr)	1.19	1.26	1.17	1.27	1.39

These changes in the patterns of final energy use are also reflected in the allocation of final energy among the various sectors of the economy. Tables 8.23A and 8.23B show how the final energy is shared between the sectors in the two scenarios. In both scenarios the energy use in transportation, households and services decreases, while the use of final energy in industry (agriculture, construction and manufacturing) increases. This is consistent with the useful and final energy demands assessed by the Higher and Lower demand projections in Chapter 5. However, in Chapter 5 the transportation sector demand was expressed in terms of energy services; the other sectors' demand levels were expressed in useful and final energy.

Table 8.23A. Final Energy Shares by Sector, Hard Solar Scenario (Higher Demand Projection), 1975 to 2100 (%)

Sector	Base Year 1975	Scenario 2000	2030	2060	2100
Transportation	19	19.4	16.0	12.9	12.1
Agriculture, Construction and Manufacturing	47	52.8	56.3	63.7	67.3
Households/Services	34	27.8	27.7	23.4	20.6
Total (TWyr/yr)	1.19	1.52	1.82	2.20	2.81

Table 8.23B. Final Energy Shares by Sector, Soft Solar Scenario (Lower Demand Projection), 1975 to 2100 (%)

Sector	Base Year 1975	Scenario 2000	2030	2060	2100
Transportation	19	18.4	11.8	10.7	10.2
Agriculture, Construction and Manufacturing	47	51.1	53.8	57.1	60.0
Households/Services	34	30.5	34.4	32.2	29.8
Total (TWyr/yr)	1.19	1.26	1.17	1.27	1.39

In the previous chapter we investigated the exact nature of this interface between energy supply and demand. We saw that the infrastructural changes of energy end use--the changes in final energy forms and their uses--can lead to both higher and lower efficiencies (in fulfilling a given demand category) relative to fossil energy forms. Therefore, the next three tables compare the assessed energy demands for the year 2100 with the actual amounts of final energy delivered in the two scenarios. The correspondence between demand and supply is obvious only if the relative performance of final energy forms supplied to end use is compared to performance of replaced fossil final energy forms (see Tables 7.2, 7.5, 7.6 and 7.7).

Table 8.24 shows the energy end use in agriculture, construction and manufacturing for the two scenarios and the

Table 8.24. Energy Use in Agriculture, Construction and Manufacturing, 2100

	Hard Solar Scenario				Soft Solar Scenario			
	Higher Demand Projection		End Use Balance		Lower Demand Projection		End Use Balance	
Use	Energy Form	(GWyr/yr)	Final Energy	(GWyr/yr)	Energy Form	(GWyr/yr)	Final Energy	(GWyr/yr)
Thermal Low	Fossil Useful	524.2	Biomass	87.9	Fossil Useful	160.5	Biomass	13.8
			Hydrogen	449.3			Biomass Co-generation	68.4
							Active Co-generation	54.8
							Solar-Thermal	55.5
Thermal High	Fossil Useful	315.0	Hydrogen	59.9	Fossil Useful	94.6	Hydrogen	1.7
							Solar-Thermal	70.5
							Electric	50.6
Steel Production	Coke Final	83.9	Coal	2.0	Coke Final	43.7	Coal	1.0
			Hydrogen	59.9			Hydrogen	31.2
Feedstocks	Oil/Gas Final	518.0	Methanol	518.0	Oil/Gas Final	216.3	Methanol	216.3
Motor Fuels	Oil/Gas Final	162.9	Hydrogen	81.5	Oil/Gas Final	104.8	Hydrogen	52.4
Electricity	Electric Final	374.0	Electric	374.0	Electric Final	215.9	Biomass Co-generation	27.8
							Active Co-generation	34.1
							On-Site Solar	54.8
							Electric	99.2
			Total	1887.6			Total	832.1

corresponding energy demand projections. The Higher demand projection for low temperature heat (thermal low) for water heating and steam generation is 524.2 GWyr/yr useful energy. 537.2 GWyr/yr final energy are supplied in the Hard Solar scenario to meet this demand (87.9 GWyr/yr biomass and 449.3 GWyr/yr hydrogen). This corresponds to a final to useful energy conversion (ratio) of 98 percent (85 percent for biomass and 100 percent for hydrogen given in Table 7.6). Taking coal as a reference fossil fuel, 616.7 GWyr/yr final energy would have been required due to its relatively low conversion efficiency of 85 percent. Thus the substitution of fossil fuels by biomass and hydrogen has caused an effective reduction in final energy requirements. Similarly, a reduction of 14 percent is achieved by a change from coke to hydrogen (with 2 percent coal added) in steel production. Especially dramatic is the reduction in the motor fuels supply, 50 percent less final energy is required because hydrogen is twice as efficient as oil products and natural gas (see Table 7.5). In some cases the energy requirements have not changed with respect to demand projection. For example, high temperature heat (thermal high) requirements for furnaces are the same since hydrogen can be converted into useful heat with virtually no losses.

The correspondence between the Lower demand projection and the Soft Solar scenario can be established in a similar way. However, the situation is more complex since many final energy forms supply a given demand category. For example, biomass co-generation delivers 68.4 GWyr/yr of final low temperature heat and 27.8 GWyr/yr of electricity. In particular, 67.8 GWyr/yr of the 160.5 GWyr/yr of useful energy demand for low temperature heat is supplied by 13.8 GWyr/yr final energy equivalent of biomass and 68.4 GWyr/yr of biomass co-generation (at conversion efficiencies of 85 and 82 percent, respectively, see Table 7.6). The remaining 92.7 GWyr/yr of useful energy demand is covered by solar active co-generation and solar thermal (small STEC) plants. Taking the same conversion efficiency as for coal, it is easily seen that the demand is fulfilled. Assuming that coal were used to supply all of the low temperature heat demand, 188.8 GWyr/yr of final energy would have been required. In the Soft Solar scenario 192.5 GWyr/yr are actually delivered. Thus, while in the Hard Solar scenario the useful low temperature heat demand was delivered more efficiently than would have been possible by fossil fuels, we see that in the Soft Solar scenario the opposite is the case. However, this apparent reduction in efficiency is an illusion to some extent. On-site solar energy sources have no obvious final energy equivalent, since most of them deliver useful heat without an intermediary final energy form. Thus it is correct to say that active solar co-generation and solar thermal plants contribute 92.7 GWyr/yr of useful energy; the final energy equivalent of 110.3 GWyr/yr given in Table 8.24 is a construct that is necessary in order to make all numbers comparable (in terms of final energy equivalent). This is not the case in the Hard Solar scenario, the 449.3 GWyr/yr of hydrogen delivered to low temperature heat is the actual final energy of hydrogen after transportation and distribution. This example illustrates that it is important to observe that local and on-site energy sources deliver useful energy and have no obvious final energy equivalent correspondence. With this observation it is not hard to verify that final energy delivered to other demand categories in the two scenarios actually corresponds to the projected demands.

In a similar way the correspondence between supply and demand can be established for energy use in transportation given in Table 8.25. Here the demand categories are specified in terms of energy service (required ton-kilometers or vehicle-kilometers). In both scenarios these energy services are supplied by the same final energy forms. All free-range vehicles use hydrogen, otherwise electricity is used. For example, the final energy use in freight transportation by train is 11 GWyr/yr. By 2100 all trains are powered by electricity compared to 66 percent in 1975 (see also Table 5.11). Taking the energy intensity of electric powered trains in the Hard Solar scenario of 6.6 Wyr per 1000 ton-kilometers (20 Wyr per 1000 ton-kilometers if diesel is used, see Tables 5.13 and 7.5A, and 66 percent less if electricity is used, see Table 7.5B), this exactly corresponds to the demanded 1683.9 x 10^9 ton-kilometers of energy service. In a similar way all other energy services in the transportation sector are fulfilled.

Table 3.25. Energy Use in Transportation, 2100

	Hard Solar Scenario			Soft Solar Scenario		
	Higher Demand Projection	End Use Balance		Lower Demand Projection	End Use Balance	
Use	Energy Service	Final Energy	(GWyr/yr)	Energy Service	Final Energy	(GWyr/yr)
Freight	(10^9ton-km)			(10^9ton-km)		
Truck	3882.9	Hydrogen	155.8	2035.4	Hydrogen	60.8
Train	1683.9	Electric	11.0	1840.3	Electric	9.7
Barge	845.4	Hydrogen	17.0	551.4	Hydrogen	10.9
Passenger	(10^9vehicle-km)			(10^9vehicle-km)		
Car	2649.3	Hydrogen	82.3	1606.1	Hydrogen	27.7
Bus	65.7	Hydrogen	11.1	32.5	Hydrogen	4.3
Train	30.1	Electric	20.6	21.5	Electric	11.2
	(10^9seat-km)			(10^9seat-km)		
Plane	1485.8	Hydrogen	42.5	990.7	Hydrogen	17.4
		Total	340.3		Total	142.0

Finally, Table 8.26 gives the energy use in households and services. Here again the actual final energy supply for each demand category resembles the pattern shown in Table 8.24 for the agriculture, construction and manufacturing sectors. In the Hard Solar scenario hydrogen and electricity supplied by central distribution grids fulfill all demand categories. In the Soft Solar scenario, on the other hand, on-site sources are used extensively. They include passive and active solar heating and photovoltaic arrays. Hydrogen is not used at all and only small amounts of electricity are supplied by central grids (60.9 GWyr/yr for specific electricity uses and another 16.1 GWyr/yr through heat pumps for space heating). The correspondence between demand and final energy delivered to end use can be verified in the same way as was done for the agriculture, construction and manufacturing sectors. Here again it can be observed that the efficiency of final energy use for heating purposes is much higher in the Hard Solar scenario (less final energy is supplied for a given useful energy demand) than in the Soft Solar scenario (where more final energy equivalent is supplied for a given useful energy demand).

Thus the final energy end use of the two scenarios shows that large differences persist in the structure of the two energy systems starting from utilization of primary energy all the way to energy use.

While the pattern of final energy delivered to fulfill the transportation demand projections was the same in the two scenarios, final energy use in all other sectors showed completely different patterns. In the Hard Solar scenario hydrogen and electricity became the most extensively used energy forms leading to significant improvements in energy end use efficiencies compared with the current energy system. In the Soft Solar scenario a switch to user-oriented energy systems caused a general decrease in the efficiencies of final energy equivalent end use. Although we have mentioned that this apparent decrease of final energy use efficiency is due to the lack of an obvious final energy correspondence of the on-site and local energy sources, this fact nevertheless illustrates the large differences between the two scenarios. Their difference is so great that even the

Table 8.26. Energy Use in Households and Services, 2100

	Hard Solar Scenario				Soft Solar Scenario			
	Higher Demand Projection		End Use Balance		Lower Demand Projection		End Use Balance	
Use	Energy Form	(GWyr/yr)	Final Energy	(GWyr/yr)	Energy Form	(GWyr/yr)	Final Energy	(GWyr/yr)
Space Heating	Fossil Useful	307.3	Hydrogen	102.3	Fossil Useful	114.5	District Heat	34.4
			Electric	68.2			Electric Heat Pump	16.1
							Passive Solar	30.0
							Active Solar	58.4
Water Heating	Fossil Useful	138.0	Hydrogen	138.0	Fossil Useful	94.9	Active Solar	146.1
Electricity	Electric Final	270.0	Electric	270.0	Electric Final	128.5	Electric	60.9
							Photovoltaics	67.6
			Total	578.5			Total	413.5

comparison of energy balances is not obvious at the final energy level of the energy system.

These drastic changes in the final energy forms and their uses in the scenarios all indicate that the sustainable energy systems in 2100 are very different from the current one from the perspective of the user. 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 two scenarios appears to require changes of no lesser magnitude than those that took place during the last 100 years.

9. CONSISTENCY WITH THE GLOBAL AND NATIONAL LEVELS AND WITH THE NUCLEAR OPTION

Comparison with the FRG and Region III

Throughout the analysis of possible energy futures for Western Europe the Global Study and in particular the results for Region III have served as a consistency check. In fact, the population and economic growth projections used in both Solar scenarios were based on the assessment of the future evolution of Region III beyond the time horizon of the Global Study, i.e. the year 2030. In that sense the two most basic scenario assumptions represent a top-down approach--a disaggregation of Region III.

At a more general level the Global Study served as a guide for the formulation of the overall objectives of the Solar Study. The scenarios were extended well into the second half of the 21st century, precisely because the conclusions of the Global Study have shown that sustainable energy systems could not be effected before 2030. Yet it was clear that the developed regions would be in a better position to master such a transition than the rest of the world. In the Global Study Western Europe as a part of Region III was the major importer of fossil energy by 2030 in direct competition with the developing parts of the world (see Figure 2.7). Thus the achievement of the reduction and eventual elimination of the Western European dependence on further fossil energy imports gains more importance when viewed within the global context.

At a different level of disaggregation an obvious question is what the results of the two solar scenarios imply for a specific country within Western Europe. In Chapter 3 we have emphasized that although Western Europe could be viewed as a relatively homogeneous partition of Region III, it is in fact by no means an entirely homogeneous entity. In order to account for some of the differences between individual countries, Western Europe was grouped into three more homogeneous areas (North, Central and South). Nevertheless, there exists no obvious mechanism for the translation of the results of the two scenarios into specific implications at the national level. A recently completed IIASA Energy Systems Group study for the BMFT (Energy

Systems Group, 1982) investigated the possibility of such a translation of the Global scenarios for the FRG. Instead of undertaking such a complex analysis, we will compare the results of the Solar Study with a specific scenario for the FRG formulated for the Enquete Kommission (Faude et al., 1980). This scenario, labeled Energiepfad 3A, is based on different specific assumptions about the future development of the energy system of the FRG than those made in the Solar Study. The Energiepfad 3A was one of four alternative scenarios designed to investigate national energy and economic development over the time horizon of 50 years, up to the year 2030. This scenario is most similar to the Solar scenarios in terms of the high energy conservation in Energiepfad 3A and a parallel introduction of renewable energy sources. This aspect of the three scenarios (Global Low, Western Europe, and FRG) marks the usefulness of the comparison--it illustrates a possible difference between national aspirations and regional, collective interests with basically similar economic growth and energy use assumptions.

Table 9.1 compares the most important scenario indicators of the three scenarios for the FRG, Western Europe and Region III, based on different objectives but with similar overall assumptions. The Energiepfad 3A indicates that already today the FRG has reached a stable population level and projects a population decline in the future. Between 2000 and 2030 an average population decline of 0.4 percent per year is assumed while in the solar scenarios the population of Western Europe and Region III still grows at 0.4 percent per year. This leads to a relative decline of the FRG share in Western European population from 15.4 percent in 1975 to 9.3 percent in 2030. Western Europe as a whole maintains an almost constant share of the population in Region III, declining from 72 to 70.1 percent over the same period. It is interesting to note that at the declining population levels the FRG continues to maintain adequate economic growth, so that its relative share in Western European GDP declines from 23.5 percent to not less than 19.1 percent. The opposite is the case for the Western European GDP share in Region III, it declines more rapidly than its population share,

Table 9.1. Summary of Important Indicators for Scenarios, FRG, Western Europe and Region III, 1975 to 2030

	Base Year			Scenario					
	1975			2000			2030		
Indicator	FRG[a]	W.E.[b]	R-III[c]	FRG[a]	W.E.[b]	R-III[c]	FRG[a]	W.E.[b]	R-III[c]
Population (10^9 people)	0.06 (15)	0.40 (72)	0.56	0.06 (12)	0.48 (70)	0.68	0.05 (9)	0.54 (70)	0.77
GDP (10^{12}\$75)	0.42 (24)	1.78 (75)	2.39	0.65 (20)	3.20 (71)	4.50	0.90 (19)	4.70 (69)	6.80
Primary Energy (TWyr/yr)	0.32 (21)	1.53 (68)	2.26	0.37 (16)	2.29 (68)	3.39	0.37 (12)	3.20 (71)	4.54
Final Energy (TWyr/yr)	0.26 (22)	1.19 (75)	1.59	0.25 (16)	1.52 (64)	2.39	0.23 (13)	1.82 (61)	2.99

a) Enquete Kommission, Energiepfad 3A for the FRG (with nuclear energy): Numbers in parentheses represent percent of Western Europe.

b) Hard Solar scenario for Western Europe: Numbers in parentheses represent percent of Region III.

c) Global low scenario for Region III.

from 74.5 percent in 1975 to 69.1 percent in 2030. In other words, Western Europe is projected to realize lower levels of economic growth than Japan, Australia and other non-European countries of Region III, but the FRG, being one of the five most developed Western Europen countries in 1975 (see Figure 3.1), could potentially use this position of relative advantage to assure continuous productivity increases with a declining population.

The primary and final energy use comparison in Table 9.1 of the three scenarios is based on the Hard Solar scenario for Western Europe and the Low Global scenario for Region III. The Soft Solar scenario is not included in this comparison since it does not correspond as well as the Hard scenario to the Global Low scenario in terms of its overall assumptions.

The Energiepfad 3A, on the other hand, could be placed in this respect somewhere between the Hard and Soft Solar scenarios. Naturally, these relative "positions" of the scenarios are only approximate since (as mentioned above) an exact comparison is not possible. The fact that the primary energy consumption of the FRG compared to that of Western Europe in the Hard Solar scenario is reduced by one half indicates higher energy use efficiency in the FRG than in Western Europe as a whole (leading to a relative share decrease from 20.7 to 11.6 percent). The final energy use decreases by about the same amount, which indicates that the two energy systems (of the FRG and Western Europe) have about equivalent overall energy conversion, transportation and distribution efficiencies. However, it is worth noting that relative to the Soft Solar scenario the shares of primary and final energy of the FRG do not decrease much. The final energy use decreases to 19.7 percent and primary energy consumption to 15.7 percent of the Soft Solar scenario. These observations indicate that the energy system of the Soft Solar scenario is less efficient than that of the Energiepfad 3A. The opposite trend can be observed between the Hard Solar and the Global Low scenarios. The share of primary energy consumption of Western Europe in Region III increases from 67.7 percent in 1975 to 70.5 percent in 2030, while the final energy share decreases from 75.1 to 60.9 percent over the same period. Thus, the energy system of the Hard Solar scenario is less efficient than that of the Global Low scenario.

The reasons for these differences are more transparent in Table 9.2 showing the relative shares of primary energy sources in the scenarios. The structure of the primary energy supply is similar in the base year (1975). The FRG shows the highest relative use of coal, most likely due to relativley high endogenous resources. But also the total relative use of fossil sources is higher due to limited hydropower potential and lower use of nuclear power.

In the scenarios, in spite of the similar starting structure of energy supply, the changes are different. The major similarity, however, is the general trend to lesser use of fossil energy and an increasing deployment of alternative energy sources. Within this overall trend, the higher relative shares of coal persist in the FRG, and Region III shows lower relative reductions in oil and natural gas use. Western Europe falls somewhere in between. The reasons for these differences are obvious. The FRG expands its domestic coal use in order to substitute more expensive and imported fossil fuels; Region III, on the other hand, is more dependent on import of fossil energy. The extreme example is Japan's complete dependence on energy imports. The energy imported to Region III has to be transported over long distances mainly from the Gulf States so that oil remains to be the preferential energy source in spite of its higher price.

The increasing use of the alternative energy sources in the scenarios also portrays different trends. Although the common tendency is to use more of both nuclear, renewable and solar energy up to the year 2000, afterwards the relative positions of alternative energy sources become asymmetric. In the Energiepfad 3A both nuclear and renewable energy use increase hand in hand, whereas in the other two scenarios one alternative is favored at the expense of the other. In the Hard Solar case, solar and renewable energy sources provide more than half of all primary energy while the nuclear share shrinks to the lowest contribution of about one-tenth in total primary supplies. In the Global Low scenario exactly the opposite happens--the renewable and solar option acquires the lowest share and nuclear the

Table 9.2. Primary Energy (Equivalent) Shares, FRG, Western Europe and Region III, 1975 to 2030 (%)

	Base Year			Scenario					
	1975			2000			2030		
Energy Source	FRG[a]	W.E.[b]	R-III[c]	FRG[a]	W.E.[b]	R-III[c]	FRG[a]	W.E.[b]	R-III[c]
Coal	29.0	22.1	25.9	36.1	26.3	28.4	40.2	12.6	22.0
Oil/Gas	66.1	65.7	62.8	40.9	46.6	54.8	25.1	23.2	39.6
Nuclear	2.0	2.4	2.8	13.1	13.6	9.5	17.1	10.3	32.3
Renewable/Solar	2.9	9.8	8.5	9.9	13.5	7.3	17.6	53.9	6.1
Total (TWyr/yr)	0.32	1.53	2.26	0.37	2.29	3.39	0.37	3.20	4.54

a) Enquete Kommission, Energiepfad 3A for the FRG (with nuclear energy).

b) Hard Solar scenario for Western Europe.

c) Global Low scenario for Region III.

second largest with about one third of all primary energy.

This difference in the levels of alternative energy deployment merits further consideration. At the surface it appears to indicate a deep dichotomy between the scenarios with respect to the two classes of alternative energy sources--breeder and burner reactors on the one hand (i.e. FBRs and LWRs) and renewable (electric) and solar (thermal) options on the other. We have observed earlier (in Chapter 4) that either of these two alternative energy sources could provide sustainable amounts of energy, provided that their deployment is properly planned for. Thus they are similar with respect to their possible use as sources of continuous energy flows in the far future. However, the similarities of nuclear and solar energy become more apparent than is generally recognized today when they are both viewed as a part of a sustainable energy system. It is precisely because of these similarities that these alternatives are compared today on the basis of their possible comparative advantages or disadvantages. We will attempt to outline some of these similarities.

Neither nuclear nor solar energy can be used directly by the consumer for all of his energy needs. In order to meet the entire useful energy need exclusively on the basis of either nuclear or solar energy an intermediate storage and transport medium is required. Transport is needed to bridge the spatial separation and configuration of energy conversion and end use. Storage is needed to bridge the temporal mismatch between energy supply and demand. It is obvious that energy transport is needed for both nuclear and solar. Even if a part of the conversion takes place locally, energy transport is needed at least in the transportation sector and energy trade. It is also obvious that energy storage is needed for solar conversion during the night, and if we recall that nuclear power plants operate most economically in base load mode, storage needs become apparent here too since demand for energy has peaks.

The similarities go further: Since a secondary energy carrier is needed for energy transport and storage, the question arises what should be its characteristics. Since it should be easily storable, electricity alone cannot be used. Since it should be easily transportable it cannot be a solid either, which leaves the liquid or gaseous form. Therefore we come back again to the reason why oil products, natural gas and electricity are the preferred energy forms today.

This similarity in possible future use of nuclear and solar energy leads once more to the important role of the liquid and gaseous secondary energy forms--methanol and hydrogen--in the two schematic representations of the sustainable energy systems from Figures 7.3 and 7.4. In order to illustrate and compare these similarities and differences between the nuclear and solar options we present a Nuclear scenario based on the same structure of the sustainable energy system and the same basic assumptions as in the Hard Solar scenario.

The Nuclear Scenario

The Nuclear scenario completes the scope of possible energy futures for Western Europe that are based each on one class of sustainable energy sources. The Soft Solar scenario was based to the maximum extent possible on renewable and user-oriented energy potentials, while the Hard Solar scenario deployed mainly central solar conversion systems. The Nuclear scenario goes into the third possible direction--maximal reliance on nuclear central conversion. In that sense it could also be labeled "Hard" Nuclear scenario. In order to maintain comparability of the scenarios, the basic underlying assumptions were only modified where it was absolutely necessary. Thus, the population and economic growth are the same in the Nuclear scenario. Furthermore, it is based on the Higher energy demand projection and on exactly the same structure of the energy system as the Hard Solar scenario that was illustrated schematically in Figure 7.3. The difference between the two scenarios consists only of minor changes in the relative cost structure of the Nuclear scenario. Table 9.3 shows the relative cost increases of the Nuclear scenario in comparison to the Hard Solar (see also Table 7.9). In the Hard Solar scenario all nuclear technologies have the same factor increases as the fossil energy resources, while centralized solar technologies have no cost increases. In the Nuclear scenario this assumption is changed. Now the cost of nuclear technologies increases only by a factor of 1.8, and central solar thermal

Table 9.3. Relative Capital and Fuel Cost[a] Increases of Energy Conversion, Transportation and Distribution Technologies (Factor Increases Relative to Base Year Costs[b])

Technology[c]	Scenario			
	Hard Solar		Nuclear	
	2030	2100	2030	2100
Fossil and Uranium Resources	3.4	19.4	3.4	19.4
Fossil Conversion	1.6	3.3	1.6	3.3
Nuclear Conversion	3.4	19.4	1.8	1.8
Solar-Thermal Conversion	1	1	3.4	19.4
Biomass Conversion	1	1	1	1
Hydropower	1	1	1	1
Transportation and Distribution	1	1	1	1
Small Conversion Plants	1	1	1	1
End Use Devices	1	1	1	1

a) A 6 percent annual discount rate and a 0.5 percent annual real cost increase were imposed on all technologies. A cost factor increase of 19.4 over a period of 125 years corresponds to an annual cost increase of 2.4 percent per year.

b) All numbers represent factor cost increases relative to capital and fuel costs in the base year 1975, see Tables 7.2, 7.4, 7.5, 7.6 and 7.7.

c) On-site and other renewable potentials (e.g., wind and wave power) are not used in the Hard Solar and Nuclear scenarios.

conversion becomes more costly over the next 100 years. The cost of other technologies is not changed, so that nuclear technologies continue to have the second highest cost increases in the future, while solar thermal technologies become as expensive as fossil fuels and natural uranium (see also Table 7.9 for comparison of relative cost increases in the Soft Solar scenario). This change in relative cost increases is the only difference in assumptions between the two scenarios. The cost assumptions in the base year and performance of all technologies in the energy system remain the same as in the Hard Solar scenario (they were given in Chapter 7).

Primary Energy Consumption and Import Dependence

We will start the brief description of the Nuclear scenario results with the primary energy requirements. Table 9.4 gives the shares of different primary energy sources used and the total consumption (for comparison with the Hard and Soft Solar scenarios see Tables 8.4 and 8.5). The first thing to observe is that the Nuclear scenario also leads to sustainable use of resources by 2100.

A more careful inspection of the relative shares of three sustainable energy sources in 2100--nuclear, hydropower and biomass--reveals an almost mirror image of the Hard Solar scenario. In both scenarios hydropower and biomass are used to the same extent. In the Hard Solar scenario, the central solar technologies contribute almost 90 percent of the required energy and in the Nuclear scenario the nuclear technologies do the same. This mirror image analogy between the two scenarios goes further. In the Hard Solar scenario solar-hydrogen conversion is preferred to solar-electric conversion, primarily due to high energy storage requirements. In the Nuclear scenario the roles are reversed. The HTR-hydrogen conversion is less intensive than the FBR-electric conversion. This is caused simultaneously by the lesser energy storage requirements and the need for a relatively high share of FBRs. Their share must be higher in order to maintain the balance of fissile materials within the joint FBR-HTR fuel cycle. Specifically, FBRs must breed some plutonium in order to allow for further installation of new FBRs, and in addition

Table 9.4. Primary Energy (Equivalent) Shares, Nuclear Scenario, 1975 to 2100 (%)

	Base Year	Scenario			
Energy Source	1975	2000	2030	2060	2100
Coal	22.1	20.9	5.1	0.6	0
Oil	52.5	24.0	6.1	0.2	0
Gas	13.2	20.9	6.0	0.4	0
LWR	2.4	13.4	5.8	0	0
FBR	0	7.5	56.2	63.6	65.3
HTR	0	0	5.5	20.4	23.9
(Nuclear Total)	(2.4)	(20.9)	(67.5)	(84.0)	(89.2)
Hydropower	8.1	8.0	6.6	5.0	3.4
Biomass	1.7	5.3	8.7	9.8	7.4
Total (TWyr/yr)	1.53	2.33	3.70	5.51	7.32

they convert thorium to U^{233} in order to provide the fuel for HTRs. Thus, this shows that the ratio between FBRs and HTRs is a function of the growth rate of the total nuclear installed capacity. However, the FBRs are best suited for electricity generation, whereas the HTRs can easily produce hydrogen by on-site thermolysis since they operate at a much higher temperature.

Table 9.5 gives the cumulative resource requirements of the Nuclear scenario. It shows that all sustainable energy sources deployed in the scenarios require no net energy imports. This result, of course, implies that the endogenous natural uranium resource (corresponding to 8.5 TWyr of primary energy if used in LWRs with once-through fuel cycle) is actually used. Once the enriched natural uranium from this resource is "burned" in the LWRs, enough plutonium is produced to establish the "stock" of FBRs capable of supporting all HTRs in conjunction with some of the depleted natural uranium (left over from the LWR operation) and thorium. Thus, in this scenario the FBR plants represent the investment in the future sustainable energy system in an analogous way as the STEC plants did in the Hard Solar scenario. However, the difference from the Hard Solar scenario is that absolutely no energy imports are required by 2100 and yet the higher energy demand level can be supported. Table 9.6 shows how this import independence is achieved. In this respect the Nuclear scenario is similar to the Soft Solar scenario (see Table 8.8). The import dependence is somewhat higher during the transition to the sustainable mode of resource use, but after 2060 the imports of energy are completely eliminated.

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 relatively high energy generation densities (compared to those of the Soft Solar scenario) the energy supply is well matched to the demand patterns and levels of the Higher demand projection. The correspondence with the Lower demand projection would not have been well chosen due to the high degree of implied energy conservation and user orientation. In the Hard Solar scenario this is simply not necessary and furthermore the high degree of user orientation of the Lower

Table 9.5. Cumulative Use of Primary Energy (Equivalent), Nuclear Scenario, 1975 to 2100 (TWyr)

Primary Energy Source	Total Resource Available[a]	Scenario	
		Total Consumed	Remaining Resource or Total Imports[b]
Coal	370.9	28.5	342.4
Oil	15.8	42.5	-26.7
Gas	9.2	27.3	-18.1
LWR[c]	8.5	8.5	0
FBR[d]	1307.5	351.3	n.a.
HTR[e]		n.a.	n.a.
Hydropower	35.3	34.0	0.7
Biomass	56.3	51.5	4.8

[a] For fossil energy and LWR the total resource available represents the ultimately recoverable resources. For other renewable energy sources the numbers represent renewable potentials cumulated over 100 years (for hydropower over 120 years), as they become available (see Chapter 6 and in particular the resource summary in Tables 6.14 and 8.7).

[b] Total (cumulative) imports are represented by negative numbers.

[c] The LWR cumulative fuel consumption would also exceed the natural uranium resource, but after the exhaustion of the domestic natural uranium the advanced LWR are used and fueled by U^{233} produced in the FBR.

[d] FBR potential is based on depleted natural uranium resource of Western Europe; the potential could be even higher, but we only use the depleted uranium stockpile left over from LWR, resulting in the given estimate of this energy source. Thus the remaining resource estimate is not applicable (n.a.). The FBR can also breed U^{233} in addition to plutonium. U^{233} is converted from thorium. Thorium is assumed to be available to the extent that it is needed.

[e] The HTR cumulative fuel consumption is not accounted for in terms of energy equivalent since it is fueled by plutonium from FBR and thorium. Thorium is assumed to be available to the extent that it is needed.

Table 9.6. Primary Energy Import Dependence[a], Nuclear Scenario, 1975 to 2100 (%)

Primary Energy Resource	Base Year 1975	Scenario			
		2000	2030	2060	2100
Coal	11	0	0	0	0
Oil	95	48.7	4.4	100.0	0
Gas	8	51.0	100.0	100.0	0
Total	53	22.3	6.3	0.6	0

a) All other energy forms used in the Nuclear scenario are not imported. Energy import dependence is calculated as a fraction of imported energy in total use of a given energy source. The total import dependence represents a fraction of total imported energy in total domestic energy use of all sources.

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.

Final Energy Use

The difference and the similarity of the Hard Solar and the Nuclear scenario can be better illustrated at the level of final energy forms that are supplied to end use. It is obvious that the amount of final energy supplied must be equivalent for both scenarios, since they both must balance the same levels and patterns of final and useful energy and energy service requirements. At the same time it is clear that the actual forms of energy delivered to end use need not always be the same, e.g. low temperature heat can be provided by almost all energy forms. However, this is not the case in all energy demand categories, e.g. the feedstock for the petrochemical industry must be based on hydrocarbons. Table 9.7 shows the final energy forms delivered to end use after primary energy conversion, transport and distribution. We have mentioned above that the Nuclear scenario represents in many ways a mirror image of the Hard Solar scenario

Table 9.7. Final Energy Shares by Form, Nuclear Scenario (Higher Demand Projection), 1975 to 2100 (%)

Form	Base Year 1975	Scenario 2000	2030	2060	2100
Coal	10.1	9.8	10.6	1.6	0.1
Oil	59.5	33.7	12.1	0.4	0
Gas	16.4	28.8	11.0	0.8	0
Electricity	11.8	20.4	38.0	45.8	50.2
Biomass	2.2[a]	5.4	5.7	5.0	3.1
Methanol	0	1.3	6.2	15.7	18.3
Hydrogen	0	0.6	15.4	30.7	28.3
Total (TWyr/yr)	1.19	1.51	1.69	2.18	2.82

except that it allows for complete import independence (just like the Soft scenario), whereas the Hard Solar does not. Compared with the final energy forms delivered to end use in the Hard Solar scenario (see Table 8.16) the Nuclear scenario shows exactly the same biomass and methanol deliveries and also parallel but exchanged roles of electricity and hydrogen. Although this result may appear to be surprising, it can be easily explained. Biomass is the only solid fuel left and as a source of carbon atom cannot be substituted by any other energy form. The same is true for methanol, all of it is needed to provide feedstocks. Thus the amount of these two energy forms must be the same in both scenarios. 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 turns out that it needs a basically fixed proportion of hydrogen and electricity since all free-range vehicles rely on hydrogen as an energy source and trains on electricity.

Thus, 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 suited to operate in base load mode but they do not have seasonal variations, thus some daily 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 the 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 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, 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 in electricity form). Table 9.8 shows that the final energy use patterns are essentially unchanged with respect to the Hard Solar scenario (see Table 8.21). Thus, in the two scenarios that are based on central energy conversion systems, hydrogen and electricity together provide three-fourths of all final energy. This stresses again the importance of these two energy carriers in the future. The symmetry is perfect: Solar-thermal conversion needs the proton more as an energy carrier because it can be easily stored, and nuclear energy needs the electron 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

Table 9.8. Final Energy Shares by Use, Nuclear Scenario, 1975 to 2100 (%)

Use	Base Year 1975	Scenario 2000	2030	2060	2100
Thermal Low	42	36.6	36.2	32.9	30.6
Thermal High	14	13.3	10.9	10.8	11.1
(Thermal Total)	(56)	(49.9)	(47.1)	(43.7)	(41.7)
Steel Production	4	4.1	3.2	2.3	2.2
Feedstocks	7	8.9	12.0	16.3	18.3
Motor Fuels	21	22.6	18.4	15.6	15.0
Electricity	12	14.5	19.3	22.1	22.8
Total (TWyr/yr)	1.19	1.51	1.69	2.18	2.82

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. However, at the same time the Nuclear scenario provides for complete import independence just as the Soft Solar scenario does,but without an active role of the consumer in the energy conversion systems.

10. INVESTMENTS AND ECONOMIC IMPACTS

Evolution of Energy Costs and Prices

The infrastructural changes both in the energy system and energy use in the two 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 payment for the import of energy change. 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. The Global Study has shown that Region III would be the only one of the three developed Regions (I, II and III) that would remain to be a net energy importer by the year 2030. By the year 2100 in the Soft Solar scenario 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 import 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 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 probably cheaper labor, the cost of imported hydrogen should leave enough room for some profit for the exporting countries.

Already this question of the cost of imported hydrogen indicates that a realistic analysis of the economic impacts of the two 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 use 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.

At the same time it is obvious that the changes in market price of commodities and capital are essentially determined by short-term fluctuations of the business cycle. The list of determinants of these fluctuations is extremely large, strating from exchange rates and balance of payments all the way to taxation policy and changes in tastes and attitudes of the consumer. The explanation of the business cycle represents a large body of economic theory and econometric research today. Because of the interest in the possible long-term evolution of the energy system, and for reasons of reducing this task to a feasible dimension, we were forced to replace these complex market forces and interrelationships with exogenous cost assumptions. In order not to neglect the evolution of relative prices entirely we have assumed changes in relative costs of energy technologies (see Table 9.3). But we must observe again that in the same way as our cost assumptions do not encompass short-term price variations, they are not predictions of long-term price development 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. Although the Global Study could not be based on such an approach either, it is possible to interpret the scenarios since they are global and tackle these questions in a qualitative way. Unfortunately, because it was necessary to extend the time horizon of the solar study beyond that of the Global Study in order to achieve the transition to a sustainable energy future, the "yardstick" of the Global Study is missing after 2030. Therefore we cannot analyze, even in a qualitative way, the possibility of increasing Western European export activities to the extent that they match the 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 afford the specified energy imports.

Energy Import Cost

We can, however, compare the relative increase of payments for energy imports in total GDP given in Figure 10.1. 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 in 2060 and then decreases gradually to 4.5 percent GDP share by 2100. 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 (oil and gas, see Table 8.8). 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.

In the Soft Solar scenario 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. In terms of relative shares, in 2030 almost 85 percent of import payments are due to fossil energy imports and the remainder is due to natural uranium imports. In the Hard Solar scenario uranium imports were not needed because of sufficiently large FBR installed capacities, large enough to fuel (after fuel reprocessing) the part of LWRs not supplied by domestic uranium resources. This gradual decrease of the relative share of the 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 percent over a period of more than 50 years, and in the long run decreases

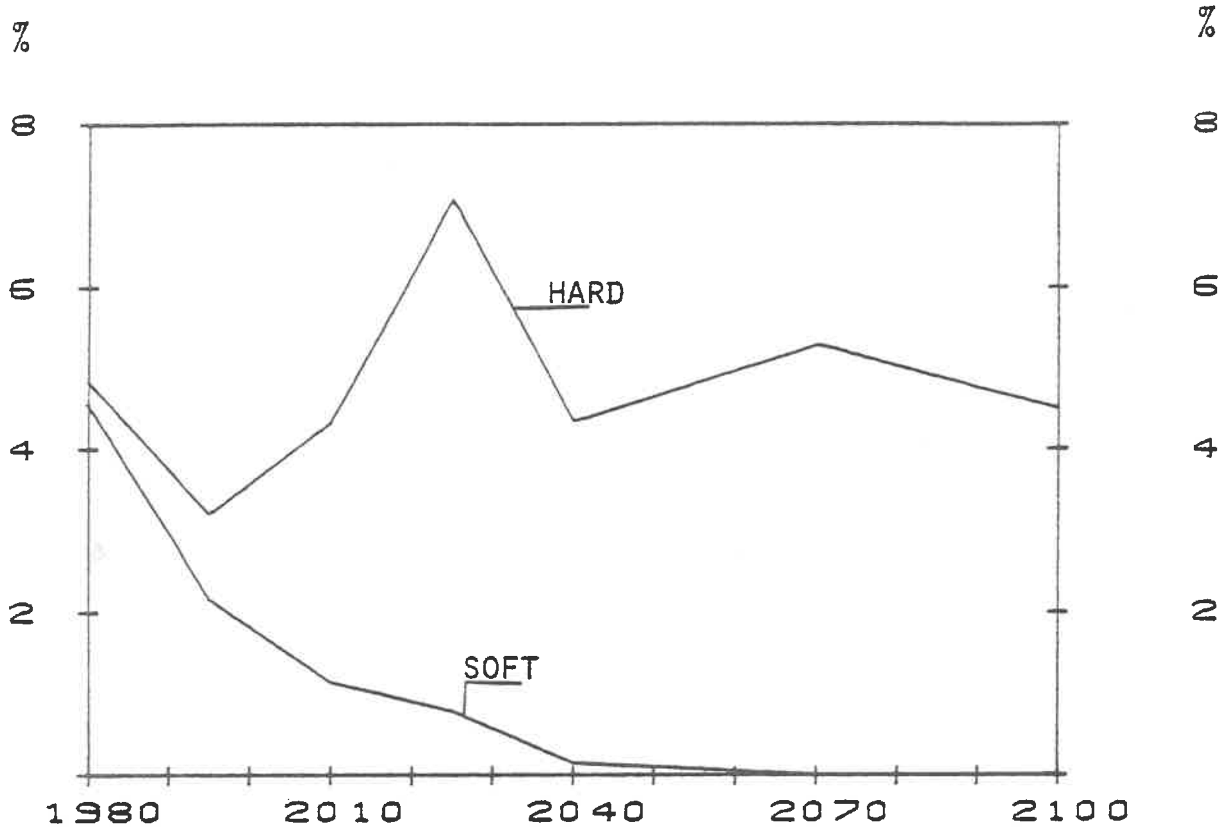

Figure 10.1. Cost of imported energy as share of GDP, Hard and Soft Solar scenarios.

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). It should be observed that the import bill in the scenarios, along with all other monetary flows, is given in real terms. Of course, the differential cost changes of energy technologies (given in Table 9.3) are reflected in the import bill. But real problems can occur when energy imports are considered in current terms and world trade prices. Depending on the base year of the real cost levels it is possible that a positive real trade balance turns into a trade deficit in current price levels. This of course also applies to the relative share of import in GDP. 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 in the long-term future, although this appears unlikely in real terms.

As a sensitivity analysis of the costs of imported energy it is also interesting to investigate the effects of relaxing our assumption of differential cost changes. In particular, the cost evolution in the scenarios favors very strongly the renewable energy sources and increases the costs of fossil and nuclear energy. However, by assuming no changes in real costs over the time horizon of the study, the import bill share in GDP is reduced quite significantly. The relative share decreases continuously to half the current level--by 2100 only 2.5 percent of GDP are paid for energy imports (as compared to 4.5 percent assuming differential cost increases).

We may conclude that the absolute increases of energy imports in the Hard Solar scenario would probably lead to negligible or at most minor impacts, provided sufficient economic growth can be sustained as was foreseen in the two scenarios (see Table 3.13). In the long run, beyond the transition away from fossil fuels, the energy import bill would take no greater share of the total GDP than today. However, problems could occur if payments for energy, foreign and domestic, clash with increasing demands for highly capital intensive energy technologies of the two scenarios. Thus we will first consider the capital requirements in the two scenarios and then the total costs of the energy system.

Investments and Capital Requirements

We have seen that the basic assumptions of the two scenarios, based on the same population and GDP growth patterns, imply an average GDP increase of 1.6 percent per year while the population grows at only 0.3 percent per year (see Table 3.16). Due to only minor changes in the economically active population (see Table 5.2) most of the GDP growth must be realized through productivity and capital intensiveness increases.

Already in the past similar trends have caused in most industrialized economies, especially in Western Europe, a continuous substitution of capital for labor. For example, in the FRG the capital-output ratio has increased by 15 percent between 1970 and 1980, reflecting a relative fall in the productivity of capital accompanied by relative increases in labor productivity. This tendency is expected to continue in the future as long as economic growth is supposed to continue as assumed in the scenarios. In particular, a shorter work week and longer annual leave could lead to lower labor participation in the production process. A large degree of user-oriented and implicit life-style changes all imply large capital investments throughout the economy. Furthermore, the extraction of practically all endogenous energy resources also demands additional capital, since less accessible resources requiring complex processing equipment must also be used. However, the change of the whole production process that leads to higher energy efficiency, assumed in the energy demand analysis, would cause a similar trend at higher capital requirements in extraction of all raw materials. A parallel trend to capital intensive infrastructural changes and resource depletion is the growing consciousness towards environmental impacts of the energy system and all economic activities. Thus energy and all other conservation measures and 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 two scenarios. Figure 10.2 compares the total investments in the energy system for the two 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 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 in Chapter 7. As all other cost assumptions in the scenarios they are also based at the 1975 price level and exchange rates in U.S. dollars. However, these investment requirements include only the capital needs of the energy system included in the energy supply model MESSAGE II. The modeled energy systems include energy conversion, transportation, distribution and end use technologies as was shown in the schematic representation in Figures 7.3 and 7.4. In particular, the capital requirement of energy extraction is not considered explicitly. The investment requirements of this part of the energy sector are determined in the IMPACT model. This model takes the primary energy production and the capacity accumulation of production, conversion, transportation and distribution technologies from the energy supply model and determines the corresponding investment needs. Special attention is given to lead times and their consequences on the timing of investment activities. They could be especially important during the next few decades since nowadays ten or more years are needed between an order of a power plant and its first commercial operation. However, since very careful timing of the future energy system configuration in the two scenarios is a prerequisite for their implementation, the long lead times must be planned for. In any case, the investment requirements determined by IMPACT indicate an additional 60 percent increase in capital needs for energy extraction

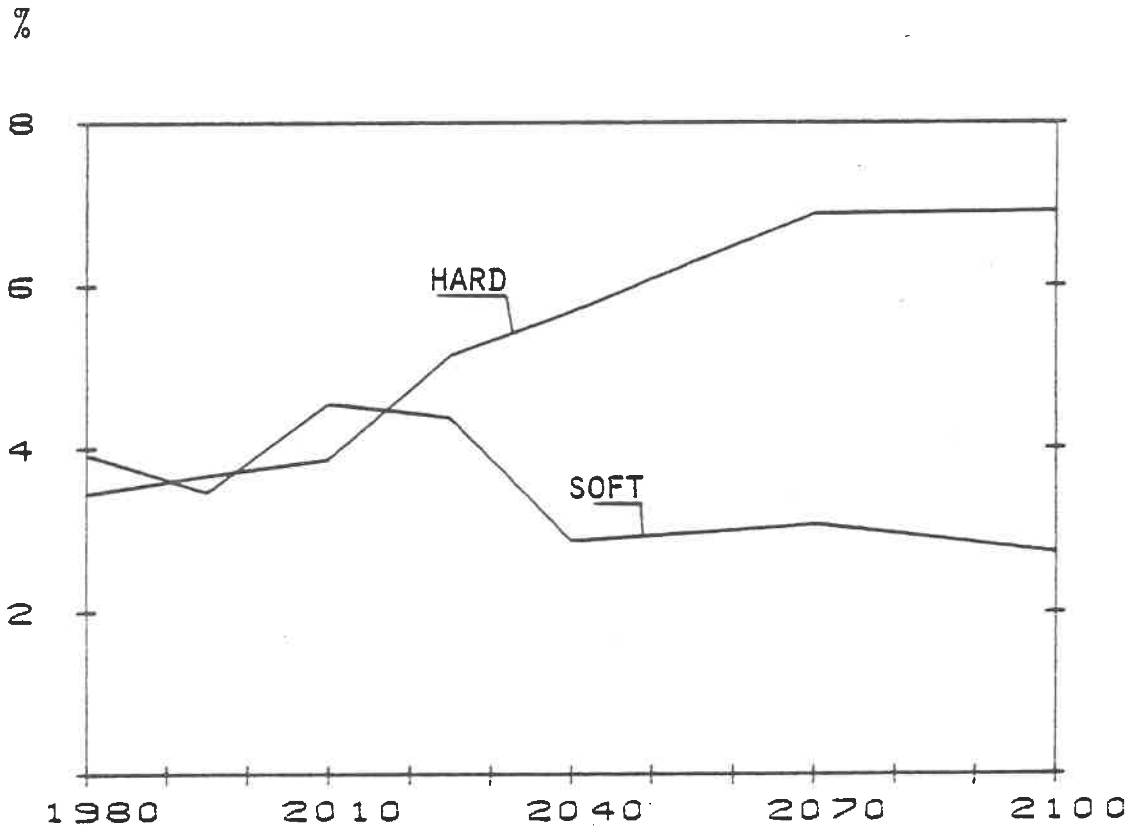

Figure 10.2. Capital requirements as share of GDP, Hard and Soft Solar scenarios.

in the year 2000. However, these additional capital needs are necessary only during the transition period and diminish drastically as the fossil and nuclear energy are phased out in the scenarios. Unfortunately, the total capital requirements in the energy sector determined by the IMPACT model do not correspond directly to those of the energy supply model MESSAGE II, since the wide spectrum of end use technologies that are extremely important, especially in the Soft Solar scenario, is not reflected accordingly. Energy extraction, conversion, transportation and distribution technologies are included in IMPACT, but not end use and on-site technologies.

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. Energy end use devices of today that are equivalent to the user-oriented technologies in the scenarios belong to the group of noncommercial energy uses and are not included in the energy accounts. In the scenarios all of the end use devices are encompassed in order to warrant direct comparison with user-oriented energy sources. Therefore a direct comparison with the published accounts of energy sector costs and those determined by the IMPACT model is not appropriate. At the same time it would not be meaningful to compare the costs of the two scenarios excluding the end use devices, since especially the Soft Solar scenario would appear to be inexpensive without its large share of user-oriented technologies.

Figures 10.3 and 10.4 show how the capital requirements in the Hard and Soft Solar scenarios are distributed between energy conversion, transportation and distribution, and energy end use. For the Soft Solar scenario the capital requirements for energy end use technologies are further disaggregated to illustrate the difference between the more conventional energy end use devices that are supplied by central energy conversion systems and the

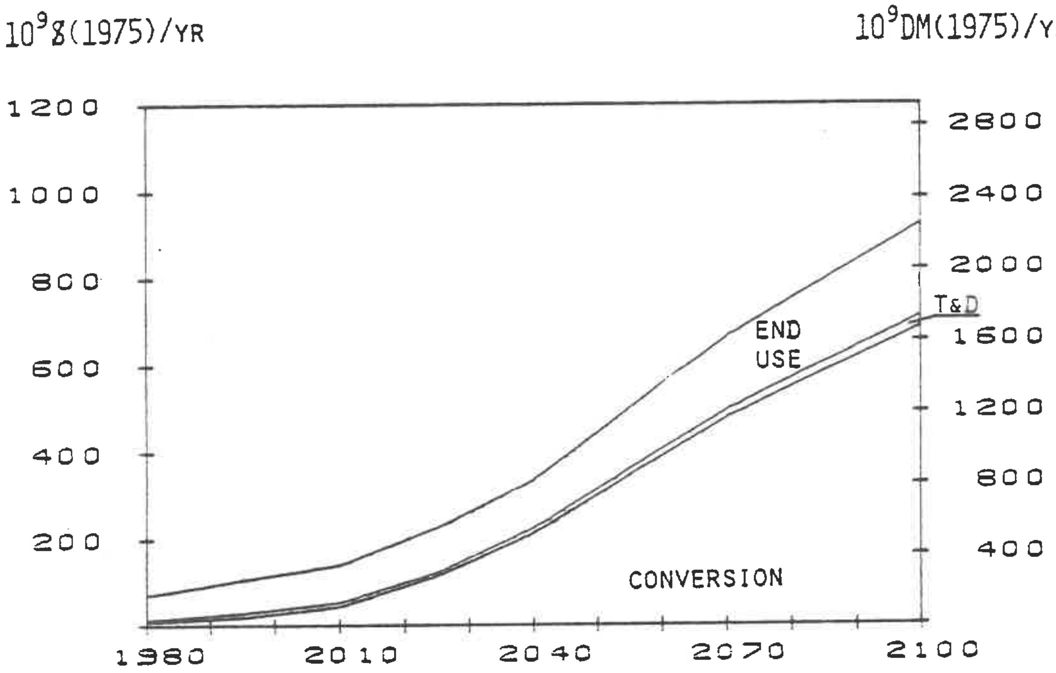

Figure 10.3. Capital requirements for conversion, transport and distribution (T&D), and end use, Hard Solar scenario.

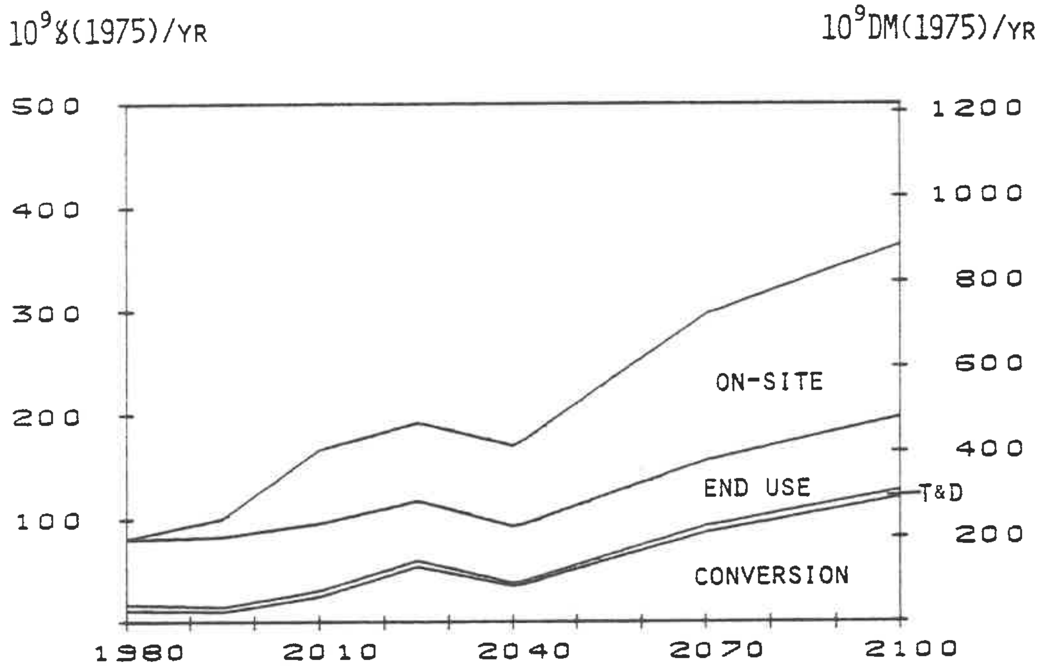

Figure 10.4. Capital requirements for conversion, transport and distribution (T&D), end use, and on-site, Soft Solar scenario.

on-site energy conversion and end use. The first group is simply labeled end use and the second on-site.

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 comlex during the next century. It should be observed that central conversion capital requirements increase more than those of end use. In the Soft Solar scenario the on-site energy becomes the most capital intensive part of the energy system accounting for almost one half of all capital requirements. Thus the structure of capital needs of the energy sector shows 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. Figure 10.5 shows the investment share in GDP for the Hard Solar scenario (from Figure 10.2) disaggregated into domestic and foreign capital needs. The share of foreign investment rapidly increases after 2030 to result in almost one half of all capital needs of the energy sector. Investing almost half the capital allocated to energy outside Western Europe toward the end of the next century certainly appears problematic, to say the least. However, such large foreign investments could be viewed as an alternative to even larger import and continuous dependence on even more expensive fossil fuels. Thus, large domestic and even foreign investments could be considered as an alternative to an even higher import bill. After all, if it is assumed that the conversion facilities built by Western Europe in the Sahara would be available as an energy source over the whole life time of the installations, then there is practically no difference between domestic and foreign investments. 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 would be offset by the increased economic activity connected with such large construction programs. These issues are very difficult and resemble somewhat those involved today

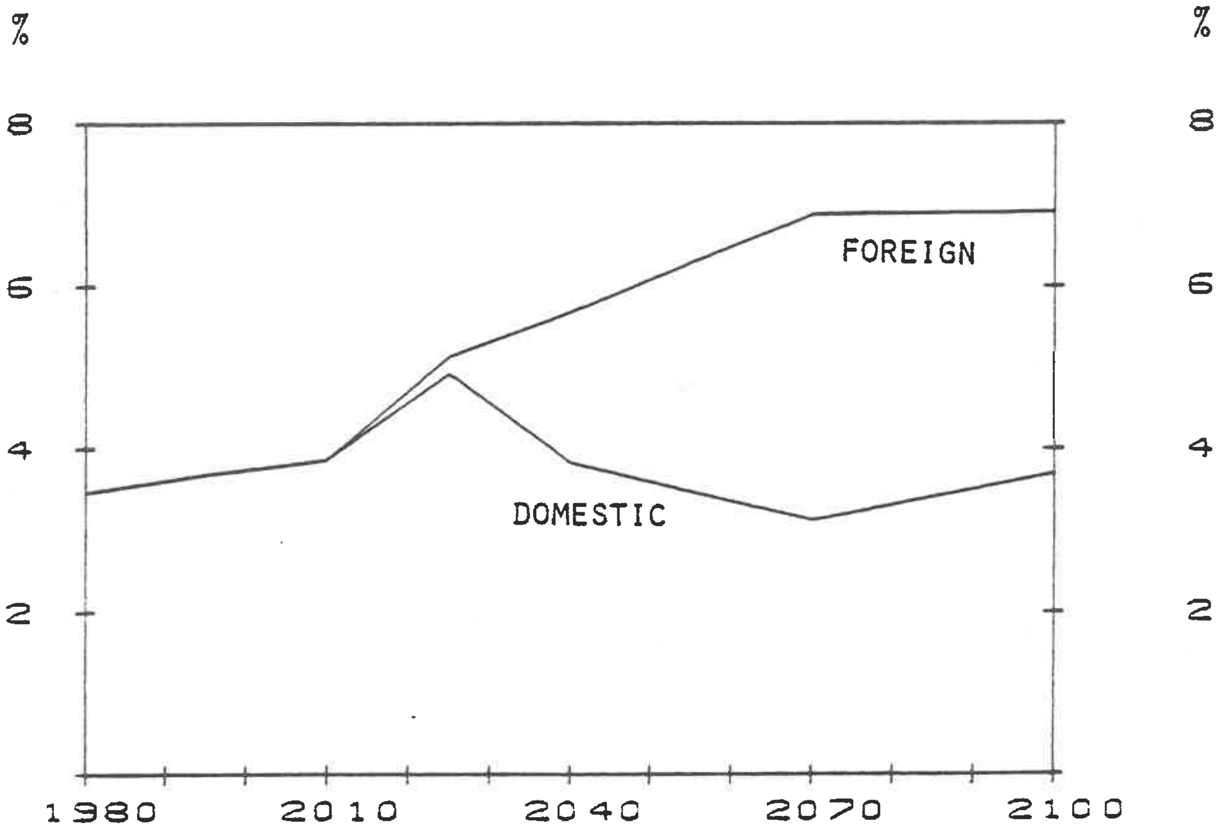

Figure 10.5. Capital requirements as share of GDP, domestic and foreign, Hard Solar scenario.

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 analysis of the capital requirements in the two scenarios has illustrated the increasing shares of end use and on-site energy technologies in total capital needs. This trend illustrates 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 life-style changes and infrastructural changes. Certainly, also these aspects of more efficient energy use are also associated with higher capital requirements throughout the economy. For example, the higher cost of more efficient urbanization patterns or restructured production processes also imply higher capital investments. However, these structural changes are so numerous in the scenarios that they cannot be all 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 assumed GDP level and structure. 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 definite 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.

Energy System Costs

The investment requirements and energy import bill are not the only costs of the energy sector. Domestic fuel costs and the expenditures for the operation and maintenance of the energy system complete the list of charges of the energy sector against the economy. They are also expected to follow the upward trend in the future. Figures 10.6 and 10.7 show the evolution of all costs in the two scenarios. In the Hard Solar scenario, operation and maintenance costs of solar installations in the Sahara are included in the total cost. Thus all three classes of expenditures for energy--capital requirements, total fuel, and operation and maintenance costs--have a domestic and foreign component in this scenario. In the Soft Solar scenario only fuel is imported during the transition period. Thus, by 2100 all costs of the energy sector are domestic in this scenario. Since the renewable and on-site energy sources have no obvious analogue to fuel costs, the domestic fuel costs include the payments for fossil and nuclear fuels until their phase-out and in addition to the cost of biomass. By 2100 the fuel costs are somewhat higher in the Soft Solar scenario due to the greater use of biomass.

Operation and maintenance costs are higher in the Soft Solar scenario. However, if energy generation outside of Western Europe is also considered, then the picture changes. The total (foreign and domestic) operation and maintenance costs of the Hard Solar scenario are more than two and a half times larger than those of the Soft Solar scenario. Such a direct comparison, however, is not really correct. The on-site and local energy systems have additional operation and maintenance costs that cannot be easily assessed. For example, well insulated houses require more careful maintenance by the user himself, but what is

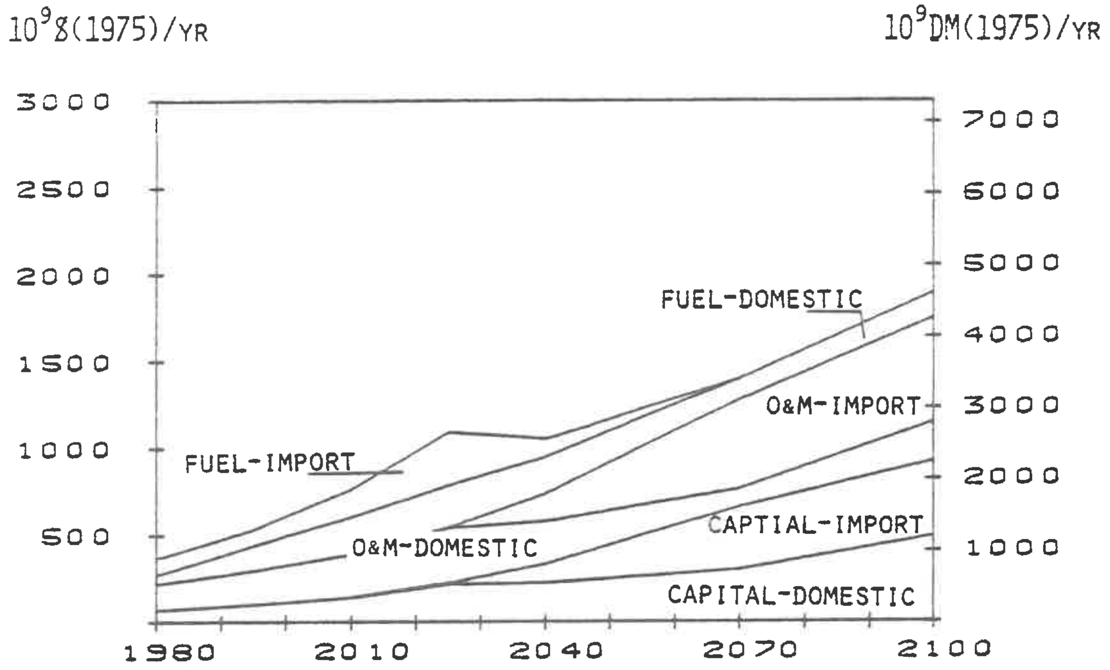

Figure 10.6. Total capital, operation and maintenance (O&M), and fuel costs, Hard Solar scenario.

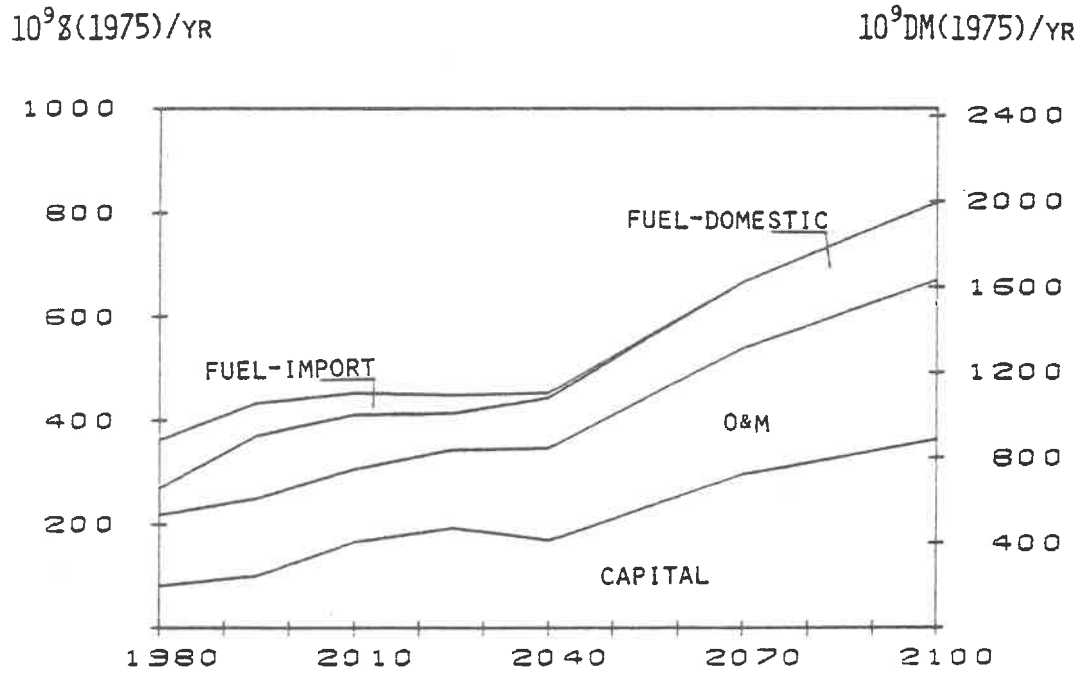

Figure 10.7. Total capital, operation and maintenance (O&M), and fuel costs, Soft Solar scenario.

more important, the new sophisticated end use devices, such as solar heating with biomass back-up, also require more operational effort by the user than, say, a single thermostat of an electric heating system. Similar observations are also true for industry and transportation. Higher energy efficiency is connected with more careful planning as well, for example, better scheduling of air and city traffic. These costs can also be seen as additional operation and maintenance costs that are not easily accountable and were not included in our estimates.

In both scenarios a strong substitution between capital and variable (fuel, operation and maintenance) costs can be observed. By 2100 the capital share in the total energy bill increases from about 20 to 49 percent in the Hard Solar and to 44 percent in the Soft Solar scenario. This observation in a sense summarizes the nature of the transition from consumptive to sustainable use of energy. Large capital investments are required in order to establish a new energy system capable of delivering the required energy on a sustainable basis. Thus capital can also replace continuous input of depletable resources. This, however, requires prudent timing and new structures both of the whole economy and also of the energy system and energy use.

Up to now we have shown the split of the total energy bill according to fuel costs (domestic and import), operation and maintenance costs (domestic and foreign), and capital requirements (domestic and foreign). However, as mentioned earlier, the current energy cost accounting does not usually include the costs and investments of energy end use. Instead, the cost of energy is determined only up to final energy deliveries. Figures 10.8 and 10.9 show the disaggregated total costs for central conversion, transport and distribution, end use, and (in the case of the Soft Solar scenario) also on-site systems. In the Hard Solar scenario end use contributes a constant share of about 30 percent to the total energy bill. In the Soft Solar scenario, on the other hand, the share of end use and on-site systems increases from 30 to over 50 percent of total costs. At the same time the share of central conversion systems in total costs increases in the Hard Solar scenario from over 40 to almost 60 percent, while in the Soft Solar scenario it remains essentially constant.

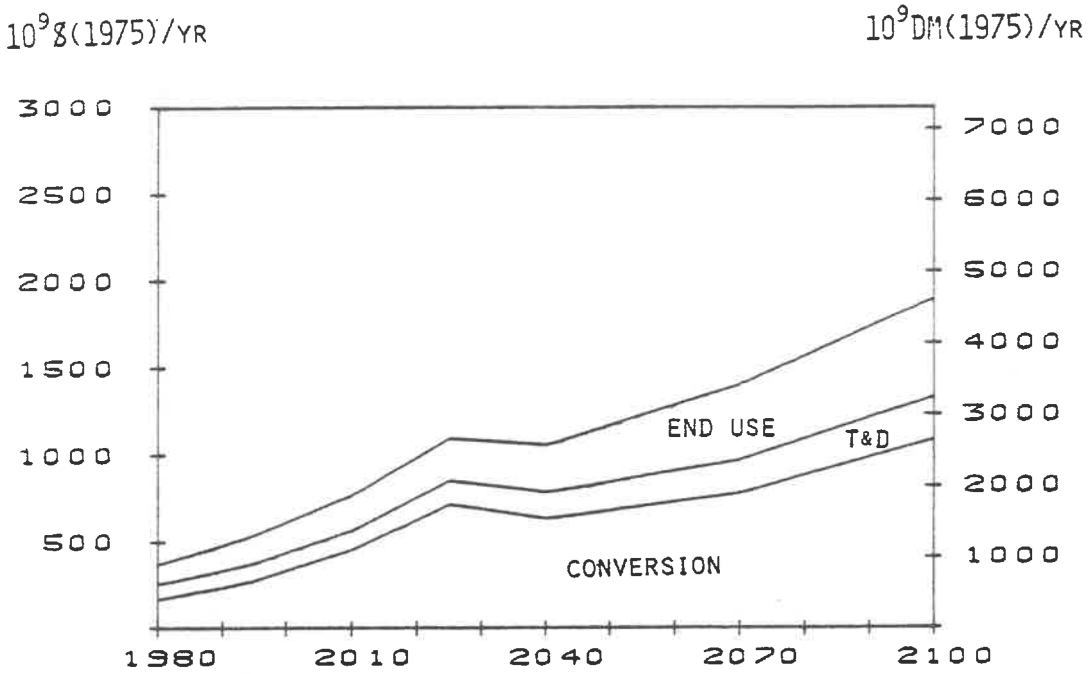

Figure 10.8. Total conversion, transport and distribution (T&D), and end use costs, Hard Solar scenario.

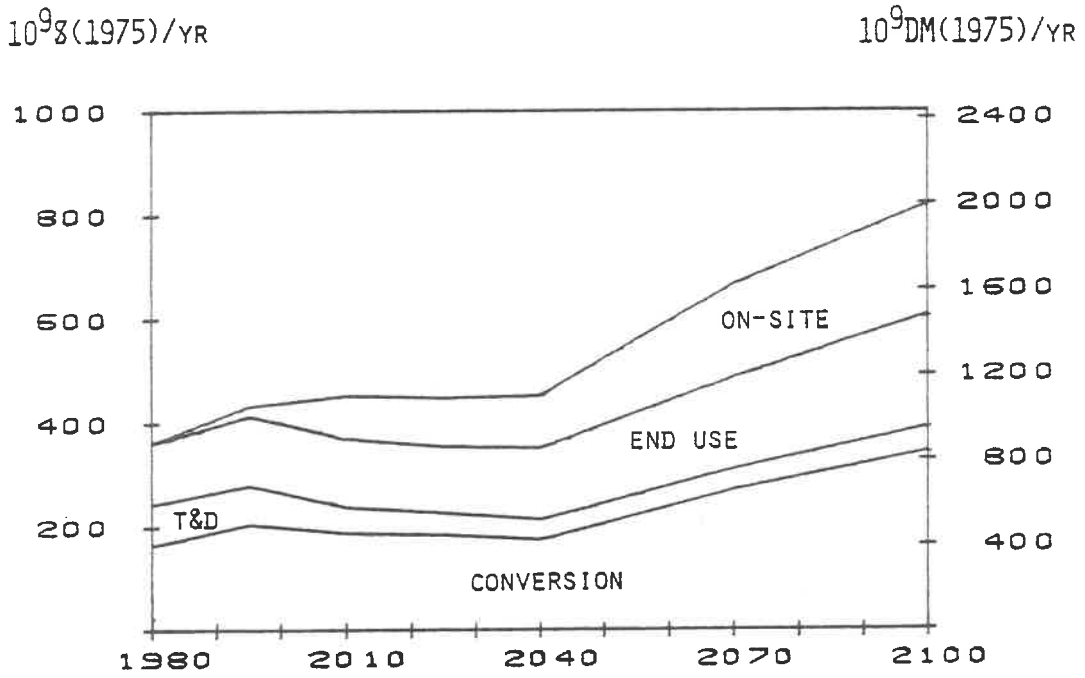

Figure 10.9. Total conversion, transport and distribution (T&D), end use, and on-site costs, Soft Solar scenario.

This again illustrates the difference between the two scenarios: the increasing role of centralized energy conversion systems in the Hard Solar scenario and of end use and on-site systems in the Soft Solar scenario.

Energy Sector and Economic Activity

Figure 10.10 shows the evolution of the total costs of the energy systems of the two scenarios as shares of GDP. In both scenarios the costs fall relative to GDP. However, one should note that these cost figures do not include any taxes, duties, profits, and so on. Like all other costs in the scenarios they do not represent market prices. Keeping in mind that taxation for some energy products alone has accounted for more than 50 percent of their selling price (e.g., gasoline taxation in almost all Western European countries), the share of the energy bill in GDP could increase accordingly due to taxation policies alone. But at the same time, the energy system costs in our scenarios include energy end use and on-site technologies which contribute initially 30 percent to total costs. In any case, the relative decrease of energy costs compared to GDP shows that large capital investments in the energy system during the next 50 years would not only lead gradually to sustainable energy use but would also lower the relative costs of energy after 2030. Table 10.1 compares the growth rates of energy costs, GDP and primary and final energy. It is interesting to observe that in both scenarios the final energy growth is lower than the cost increases, while the opposite is true for primary energy until 2030 while fossil fuels are still used. Moreover, the scenarios lead to energy use and energy cost increases well below the level of economic growth as the population levels stabilize, meaning small increases of the economically active part of the population. This was possible by a complete change of the energy system from current consumptive use of largely imported fossil energy to sustainable use of renewable energy sources. Along with such change of the energy system many parallel changes in life-styles and the economy were assumed. Whether these changes are possible during the next 100 years is an open question.

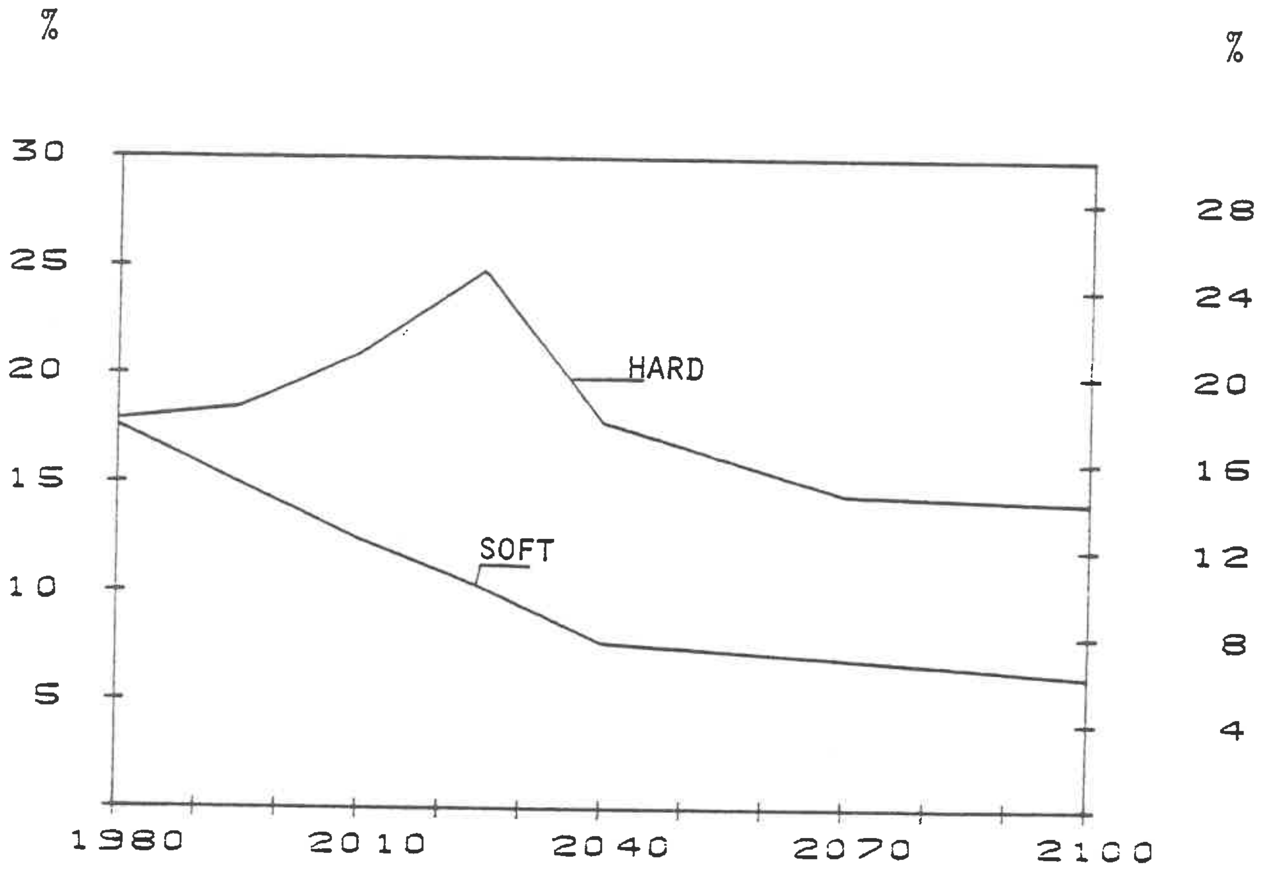

Figure 10.10. Total costs as share of GDP, Hard and Soft Solar scenarios.

Table 10.1. Annual Growth Rates of Population, GDP, Energy and Total Costs of the Energy System, Hard and Soft Solar Scenarios, 1975 to 2100 (%/yr)

	1975-2000	2000-2030	2030-2060	2060-2100
Population	0.7	0.4	0.2	0
Labor Force[a]	2.0	0.8	0.3	0.1
GDP	2.3	1.3	1.7	1.4
Primary Energy				
Hard Solar	1.6	1.1	1.1	0.6
Soft Solar	0.7	0.8	0.5	0.3
Final Energy				
Hard Solar	1.0	0.6	0.6	0.6
Soft Solar	0.2	-0.3	0.3	0.2
Total Costs				
Hard Solar	2.5	1.9	0.5	1.0
Soft Solar	1.0	0.1	0.9	0.8

a) Economically active population.

In order to investigate this question further, a general economic equilibrium model, MACRO, was applied with the assumptions embodied in the scenarios. The results, however, are not conclusive. The model includes two sectors, an energy sector and the rest of the economy. It clears the markets for energy, capital and labor by means of factor price adjustments. Thus any change in the combination of the aggregate production process is solely a response to changes in the factor prices. This means that any regulatory measures or changes in life-styles such as, for example, higher insulation standards or lower travel distances are translated into price changes. Thus the only translation of the assumed life-style changes and higher efficiencies in energy use are the relative price changes and productivity increases. For example, the determination of import and export prices is necessary for the balance of exports and imports which play an important role, especially in the Hard Solar scenario. This, however (for reasons that were mentioned above), is impossible to do over a period of 100 years or more without at least knowing something about the global trade evolution over the same period.

Given these problems in applying a general equilibrium model to the scenarios, the results show that the share of energy investments in total investments would increase by roughly 10 to 30 percent by 2100. This implies a major structural change in the composition of total output. These consequences do not even include the capital needs for an adequate end use structure. In addition, the analysis indicates that the relative share of labor to capital in the economic output would decrease, causing serious problems in income and wealth distribution.

The internal consistency between economic activity, energy use and energy prices was in the foreground of the analysis. The discrepancies mentioned before, however, limit the conclusiveness of the numerical values calculated by MACRO. Just taking the given evolution of GDP and secondary energy demand, the real energy price (above inflation) should have increased by a factor of 6.9 between 1980 and 2100. This corresponds to an annual price increase of 1.6 percent. Assuming a general inflation adjusted for the omission of energy doubling every 20 to 25 years (equivalent to 3 percent per year), the 6.9 real price increase in energy would result in an overall inflation of roughly 5.2 percent.

In the scenarios, however, energy costs are mainly based on predetermined costs and not equilibrium prices. But according to MACRO energy is not sufficiently expensive to initiate price induced energy conservation and substitution effects. Thus price induced conservation alone would not be adequate to cut down energy demand as conceived in the scenarios consistently with the cost assumptions. However, any other non-price mechanism is not reflected in this model.

This result indicates that the two scenarios basically can not be compared with respect to required investments or energy costs,since each of them implies an essentially different economic structure so that the base of comparison vanishes. In addition, the results of MACRO, based on the current economic structure, show that neither scenario could be achieved with the given assumptions under the condition of market equilibrium. This indicates that unprecedented government controls and regulations and a parallel change of consumer habits would have to take place in the future. Whether this is possible or even desirable still remains to be seen. But the analysis of the costs of the two 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 lifestyles and economic structure are consistent and possible. With the methodological tools at our disposal today the feasibility of these changes cannot be determined.

11. CONCLUSIONS AND IMPLICATIONS

The aim of the study was to investigate the possibility of a transition to sustainable energy systems based on solar energy in Western Europe. In pursuit of this objective an analytical approach was adopted involving the assessment of the two sets of assumptions that define the Hard and Soft Solar scenarios and lead to a balance of energy demand and supply. 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 sections 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 type 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 compare different economic structures and consumer habits with current measures. Due to these reasons the two scenarios should not be viewed as predictions of a likely future for Western Europe. The scenarios cannot be viewed as 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 two "yardsticks" that delimit the range of feasible and consistent futures given the assumptions. A choice between the scenarios would certainly not only 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.

At the risk of using very general and perhaps vague terms, we will outline the broad implications of the scenarios based on the specific findings of the study.

We have emphasized throughout this report that the two scenarios could be viewed as two extremes. This does not mean that the two extremes would be the only two possible alternatives among which to choose--on the contrary, the future will probably bring some aspects of each scenario and most likely many features not encompassed within this study. Precisely this was the reason for the analysis of the third scenario, based on nuclear technologies, that incorporates an intermediate degree of centralization of the energy system and serves as a comparison to the two exclusively solar scenarios. But the two solar scenarios are exclusive in one important respect: If the society should choose to go one way and not the other--if it should choose to go "soft" or "hard"--in the sense prescribed by the scenario assumptions, then over the long-term future, say after the year 2000, and especially after 2030, the social and economic structure of the scenario would tend to reinforce itself (to "attract") making it more difficult for the society to choose a significantly different option. It is hard to conceive that the life-styles and the economy of the Soft scenario could be easily changed during the second half of the next century to result in the energy supply structure of the Hard Solar scenario. This means that the vast capital and human investments necessary to achieve a "soft" future leave little room for the choice of a different road into the future once the course is taken. This is of course also true for the Hard Solar scenario. As an illustration we recall the different structure of end use systems of the two scenarios. In the Hard Solar scenario most of the end use technologies are based on hydrogen, in the Soft on the on-site and local energy sources.

In the most general terms, perhaps the central feature of the Hard Solar scenario is the broad unification of Western Europe. For example, the FRG could provide capital and technological know-how to South European countries. In that way it should be possible to guarantee a steady supply of solar derived energy and at the same time provide additional economic activities for the further development of South Europe and an eventual reduction of North to South economic differences in Western Europe. In terms of the energy system this possible unification of Western Europe means that solar insolation can match energy demand. This was possible only by central solar conversion into an energy carrier that can easily be transported over long distances and stored. The storage is a new aspect not encountered today. Long distance transportation implies a sophisticated and centralized distribution grid. This all leads to the choice of hydrogen as the preferential energy carrier. It is the only energy form in sight today that unifies all of the outlined qualities and characteristics. It has the great advantage that the current energy end use patterns could be maintained with some structural changes, e.g. hydrogen cars and aircraft, hydrogen burners for space heating, etc. This still necessitates life-style changes, higher conservation measures, but not necessarily different urbanization patterns. Hydrogen, as a high-quality fuel can be consumed at the same high population densities that are encountered today in industrialized zones of Western Europe without adverse environmental effects of coal and oil. In other words, in the Hard Solar scenario it is the energy system that establishes an interface to the end use. However, this is associated with certain physical constraints such as land availability in high solar insolation areas of Western Europe. Already the energy demand increases of the Hard Solar scenario necessitate hydrogen imports. This is precisely where the life-style changes are necessary; they must lead to relative demand reductions, more efficient energy end use but not necessarily a completely different mode of energy end use.

In a similar way the central feature of the Soft Solar scenario could be identified as the large degree of user orientation which strengthens the regionalization of Western Europe. The local surrounding gains importance in energy generation. The user himself provides the new interface between energy conversion and end use and not a utility operated energy system. He has to adjust his life-style in order to rely on many "five percent options". This does not only imply even stronger energy conservation and demand reductions, but also results in different urbanization and settlement patterns. This is a logical prerequisite due to relatively low energy conversion densities achievable by local use of photovoltaics, warm water collectors and biomass. The energy conversion and end use becomes one and the same thing--the use of energy carriers that provide the "buffer" between generation and use of energy is reduced to the bare minimum.

The Nuclear scenario completes the scope of possible energy futures for Western Europe that are based on one class of sustainable energy sources. The energy conversion, transport and distribution system is also centralized in the Nuclear scenario but it does not necessitate a unification of Western Europe as the Hard Solar scenario does. The spatial separation between the user and energy conversion facilities is smaller leading to the alleviation of some problems caused by the requirement for long-distance transport and seasonal storage of energy in the Hard Solar scenario. It is similar to the Soft Solar scenario in the sense that it also results in the elimination of all energy imports and a reliance on domestic, sustainable energy sources by the year 2100.

These broad characteristics of the scenarios were reflected throughout the analysis. The Hard Solar and Nuclear scenarios were more consistent with higher energy demand than the Soft scenario. Most of the capital burden of the Hard scenario was in central conversion systems, in the Soft Solar scenario it was in the end use systems. Thus each of the scenarios deals differently with the change of the current structure of energy system based on the fossil fuels both as a form of energy storage and energy source. In the Hard Solar scenario the "front end" of the energy chains is changed the most, while in the Soft Solar scenario the end use changes more significantly. This is also the unifying characteristic common to both solar scenarios--both imply changes in our everyday life. The future will surely bring some of the changes outlined in the scenarios. Clearly, all the aspects of these changes cannot be deduced from the analysis of the potential role of alternative and solar energy systems within Western Europe. The study does show, however, that to the extent that some considered and possibly other not considered changes do take place, they would have a decisive influence on the configuration of the future energy system. The ultimate configuration of the energy system will depend on choices made now and during the transition period. In any case, significant changes are necessary for a sustainable energy future, they must be anticipated and perhaps stimulated today. The sustainable use of resources at our disposal requires an investment before the readily available stocks are dissipated through irreplaceable flows.

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