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

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ZUSAMMENFASSUNG


THE TEMPORAL SCOPE

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

BASIC ASSUMPTIONS

The future energy outlook for Western Europe depends on a multitude of interdependent factors - most important among these are economic development and population growth. Therefore, the future evolution of Gross Domestic Product (GDP) and population are the two basic assumptions in the scenarios. Population evolution is based on projections developed by Keyfitz (1979) that indicate that Western Europe would reach a stable population of 570 million people by the end of the next century.
During this period of over 100 years, South Europe would increase its share in Western European population from 55% in 1975 to 63%, while the shares of North and Central Europe would decline from 6 to 4% and from 39 to 33%, respectively.

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

| THE ANALYTICAL APPROACH |

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

| ENERGY DEMAND AND USE |

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

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

The energy demand levels are assessed in the MEDEE-2 model for all sectors of the economy, for example industry, transport, households and services, and within each sector by demand category. For those demand categories where a number of final energy forms (usually each with a different efficiency) could provide a given service the demand levels are specified in terms of the required useful energy or energy services. Where only one specified form of final energy can provide the service, the demand levels are specified in terms of final energy, for example hydrocarbons for feedstocks in chemical industry. The energy supply model MESSAGE II then determines the structure of an energy supply system that is capable of provi-
The energy system configuration is specified by MESSAGE II so as to provide a cost minimal energy mix that meets demands under the constraints of maximal build-up rates for technologies and resource constraints. Thus, the dynamic balancing of energy demand and supply in each scenario can be divided into two parts: first, the assessment of energy demand level and the associated activities in the whole economy; second, the structure of the energy system capable of delivering the demanded energy to the consumer.

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

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

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


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

<table>
<thead>
<tr>
<th>Final Energy Form</th>
<th>Thermal Low</th>
<th>Thermal High</th>
<th>Coke</th>
<th>Feed-stocks</th>
<th>Motor Fuels</th>
<th>Electricity</th>
<th>Total</th>
</tr>
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<tbody>
<tr>
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<td>28.8</td>
<td>43.5</td>
<td>81.2</td>
<td>239.9</td>
<td></td>
<td>121.0</td>
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<td>Oil Products</td>
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<td>52.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>709.6</td>
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<td></td>
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<td>195.8</td>
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<tr>
<td>Electricity</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>141.2</td>
<td>141.2</td>
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<tr>
<td>Biomass</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>26.4</td>
</tr>
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<td>Total</td>
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<td>168.1</td>
<td>43.5</td>
<td>81.2</td>
<td>239.9</td>
<td>141.2</td>
<td>1194.0</td>
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Table 1A. Final Energy by Form and Use Base Year 1975 (GWyr/yr)

<table>
<thead>
<tr>
<th>Final Energy Form</th>
<th>Steel-Production Low</th>
<th>Steel-Production High</th>
<th>Feed-stocks</th>
<th>Motor Fuels</th>
<th>Electricity</th>
<th>Total</th>
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</thead>
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<tr>
<td>Coal</td>
<td>68.2</td>
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<td>31.6</td>
<td>164.0</td>
<td>743.8</td>
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<tr>
<td>Electricity</td>
<td>87.9</td>
<td></td>
<td></td>
<td></td>
<td>87.9</td>
<td></td>
</tr>
<tr>
<td>Biomass</td>
<td></td>
<td>518.0</td>
<td></td>
<td>390.2</td>
<td></td>
<td>518.0</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>689.6</td>
<td>59.9</td>
<td></td>
<td></td>
<td>1454.7</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>845.7</td>
<td>61.9</td>
<td>518.0</td>
<td>421.8</td>
<td>2806.4</td>
<td></td>
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Table 1B. Final Energy by Form and Use Hard Solar Scenario, 2100 (GWyr/yr)

<table>
<thead>
<tr>
<th>Final Energy Form</th>
<th>Thermal Low</th>
<th>Thermal High</th>
<th>Steel-Production</th>
<th>Feed-stocks</th>
<th>Motor Fuels</th>
<th>Electricity</th>
<th>Cogeneration</th>
<th>Total</th>
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<td>Coal</td>
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<td>1.0</td>
<td>20.9</td>
<td></td>
<td>160.1</td>
<td>96.2</td>
<td>1.0</td>
<td>247.7</td>
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<tr>
<td>Electricity</td>
<td>13.8</td>
<td>50.6</td>
<td>216.3</td>
<td></td>
<td></td>
<td></td>
<td>216.3</td>
<td>110.0</td>
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<tr>
<td>Biomass</td>
<td></td>
<td></td>
<td>31.2</td>
<td>173.5</td>
<td></td>
<td></td>
<td>206.4</td>
<td></td>
</tr>
<tr>
<td>Hydrogen</td>
<td>34.4</td>
<td>1.7</td>
<td>34.4</td>
<td></td>
<td></td>
<td></td>
<td>34.4</td>
<td></td>
</tr>
<tr>
<td>District Heat</td>
<td>344.7</td>
<td>70.5</td>
<td>32.2</td>
<td></td>
<td>194.4</td>
<td>316.6</td>
<td>96.2</td>
<td>1387.5</td>
</tr>
<tr>
<td>On-Site</td>
<td></td>
<td></td>
<td>216.3</td>
<td></td>
<td></td>
<td></td>
<td>216.3</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>409.0</td>
<td>122.8</td>
<td>156.5</td>
<td></td>
<td>316.6</td>
<td>96.2</td>
<td>1387.5</td>
<td></td>
</tr>
</tbody>
</table>

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

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

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

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

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

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

<table>
<thead>
<tr>
<th>Form</th>
<th>Base Year</th>
<th>Soft Solar</th>
<th>Hard Solar</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1975</td>
<td>2030</td>
<td>2100</td>
</tr>
<tr>
<td>Coal</td>
<td>10.1</td>
<td>4.6</td>
<td>0.1</td>
</tr>
<tr>
<td>Oil</td>
<td>59.5</td>
<td>6.6</td>
<td>0</td>
</tr>
<tr>
<td>Gas</td>
<td>16.4</td>
<td>4.2</td>
<td>0</td>
</tr>
<tr>
<td>Electricity</td>
<td>11.8</td>
<td>18.9</td>
<td>17.8</td>
</tr>
<tr>
<td>Biomass</td>
<td>2.2</td>
<td>9.8</td>
<td>7.9</td>
</tr>
<tr>
<td>Methanol</td>
<td>0</td>
<td>2.4</td>
<td>15.6</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>0</td>
<td>13.5</td>
<td>14.9</td>
</tr>
<tr>
<td>District Heat</td>
<td>0</td>
<td>2.9</td>
<td>2.5</td>
</tr>
<tr>
<td>On-Site</td>
<td>0</td>
<td>37.1</td>
<td>41.2</td>
</tr>
<tr>
<td>Total(TWyr/yr)</td>
<td>1.19</td>
<td>1.17</td>
<td>1.39</td>
</tr>
</tbody>
</table>

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

The whole structure of the energy supply system is determined by implementing the set of technologies which minimizes the overall cost of the supply system under constraints of build-up rates, resource depletion, etc. In order to use as much as possible of the specified ‘reference system’ and still allow cost minimization, a cost penalty is levied on technologies which do not belong to the ‘reference system’. The following cost penalty structure is used – 2.4 % per year cost increase of fossil resources, natural uranium and nuclear system investment costs. In addition, in the Soft Solar scenario, cost subsidies of 40 % for local and 60 % for on-site energy supply are actually awarded within the ‘reference system’. We feel that such an approach leaves more flexibility to structure the energy supply system best.
solar thermolytic hydrogen must be 
imported because the endogenous solar 
thermal potential of Western Europe is 
practically exhausted by electricity pro-
duction. Moreover, after 2030 the ener-
gy import dependence increases again in 
the Hard Solar scenario due to increased 
hydrogen needs. In the other scenario 
energy imports are completely elimina-
ted after 2060.

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

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

Thus, the drastic changes in the final 
and primary energy forms and their use 
and origin all indicate that the sustaina-
ble energy systems in 2100 are very dif-
ferent from the current one from the 
perspectives of both the user and energy 
supply infrastructure. It is possible to 
observe some analogies to the current 
system as we have outlined above, but 
they stress even more the overall diffe-
rence.

On the other hand, while these differen-
ces can hardly be overstated, the transi-
tion 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 consid-
ered to be renewable. Thus, the transition 
foreseen in the scenarios appears to 
require changes of at least a comparable 
order of magnitude to those that took 
date during the last 100 years.

ENERGY IMPORT COSTS AND 
CAPITAL REQUIREMENTS

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

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

The capital for exploiting this resource 
would be provided by Western Europe. 
Thus, although not a Western European 
energy source, the hydrogen production 
in the Sahara was considered as a part of 
the capital requirements needed to 
implement the Hard Solar scenario. 
Thus, in the Hard Solar scenario,
Western Europe has the burdens of investing in the development of hydrogen production outside its borders, and of paying for continuous hydrogen imports. The cost of imported hydrogen was assumed to be the same as that of domestic hydrogen. Due to the fact that hydrogen production in the Sahara would be cheaper than in Western Europe, because of higher solar insolation and cheaper labour, the cost of imported hydrogen should leave enough room for some profit for the exporting countries.

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

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

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

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Base Year</th>
<th>1975</th>
<th>2030</th>
<th>2100</th>
<th>2030</th>
<th>2100</th>
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<tbody>
<tr>
<td>Coal</td>
<td></td>
<td>22.1</td>
<td>2.4</td>
<td>0</td>
<td>12.6</td>
<td>0</td>
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<td>Oil</td>
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<td>52.5</td>
<td>3.6</td>
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<td>9.5</td>
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<td>Gas</td>
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<td>2.3</td>
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<td>LWR</td>
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<td>FBR</td>
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<td>0</td>
<td>9.5</td>
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<td>HTR</td>
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<tr>
<td>(Nuclear Total)</td>
<td></td>
<td>(2.4)</td>
<td>(4.6)</td>
<td>0</td>
<td>(10.3)</td>
<td>(0)</td>
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<td>Hydropower</td>
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<td>10.6</td>
<td>8.5</td>
<td>7.7</td>
<td>4.3</td>
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<tr>
<td>Biomass</td>
<td></td>
<td>1.7</td>
<td>8.4</td>
<td>15.1</td>
<td>10.1</td>
<td>9.4</td>
</tr>
<tr>
<td>Windpower</td>
<td></td>
<td>0</td>
<td>34.8</td>
<td>33.9</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Wavepower</td>
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<td>0</td>
<td>1.8</td>
<td>1.4</td>
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<tr>
<td>Photovoltaics</td>
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<td>0</td>
<td>6.0</td>
<td>9.4</td>
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<tr>
<td>On-Site Sources</td>
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<td>0</td>
<td>25.4</td>
<td>28.3</td>
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</tr>
<tr>
<td>(‘Soft’ Total)</td>
<td></td>
<td>(0)</td>
<td>(68.0)</td>
<td>(73.0)</td>
<td>(0)</td>
<td>(0)</td>
</tr>
<tr>
<td>Solar-Electric</td>
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<td>0</td>
<td>0</td>
<td>19.9</td>
<td>3.4</td>
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<tr>
<td>Solar-Hydrogen</td>
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<td>0.1</td>
<td>3.4</td>
<td>6.2</td>
<td>82.9</td>
</tr>
<tr>
<td>(‘Hard’ Total)</td>
<td></td>
<td>(0)</td>
<td>(0.1)</td>
<td>(3.4)</td>
<td>(36.1)</td>
<td>(86.3)</td>
</tr>
<tr>
<td>Total(TWyr/yr)</td>
<td></td>
<td>1.53</td>
<td>2.36</td>
<td>3.16</td>
<td>3.2</td>
<td>5.76</td>
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</table>
In the Soft Solar scenario the energy import bill is very low. Already by 2030 less than 1 % of total GDP goes for energy imports, and by 2100 no energy is imported. This gradual decrease of the relative share of energy imports and eventual import independence in the Soft Solar scenario can only have positive effects on the total balance of payments and overall economic growth. However, even in the Hard Solar scenario the relative share of energy imports in GDP increases less than 50 % over a period of more than 50 years, and in the long run decreases below the current level. This should probably not cause any critical problems. It represents at most a doubling over the current energy import bills of most of the Western European countries (for example in the Federal Republic of Germany the share of energy imports in GDP was 3.1 % in 1975).

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

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

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

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