Ecofys the Netherlands BV
P.O. Box 8408
NL-3503 RK Utrecht
Kanaalweg 16-G
NL-3526 KL Utrecht
The Netherlands
www.ecofys.nl

T +31 (0)30 280 83 00
F +31 (0)30 280 83 01
E info@ecofys.nl

CONCENTRATING SOLAR POWER FOR FUEL CELL VEHICLES

- Confidential -

Utrecht, August 2006
PDCSNL061208

Erika de Visser
Robert van den Hoed
Henk Barten

By order of the:
Milieu- en Natuurplanbureau (MNP)
The Netherlands

Foreword

In the Netherlands, the Milieu- en Natuur Planbureau (MNP)[1] currently carries out an evaluation of the transition policy as conducted between 2001 and 2006. The transition policy of the NMP4 (Fourth National Environmental Action Plan) is set to stimulate system changes on the long term (2040) which will substantially reduce the environmental burden of energy use.
As part of the objectives various energy sources and energy carriers that would possibly fit in these objectives are being evaluated. Therefore the possible role of renewable energy in clean transport is a major subject.

By order of MNP, Ecofys has performed this study which focuses on the potential of solar energy in transportation, and using hydrogen as an energy carrier. The evaluation includes the technical, economical and environmental aspects of solar energy and the hydrogen fuel chain. Furthermore the transition process is evaluated, over the full chain from solar energy to the use of hydrogen in fuel cell vehicles. For the technical assessment of concentrating solar power potential, Deutsches Zentrum für Luft und Raumfahrt (DLR) was involved as a subcontractor.

This study has been supervised by Dick Nagelhout and Jan Ros of the MNP.

[1] English name: Netherlands Environmental Assessment Agency (MNP).

Summary

This report provides a feasibility study of Concentrating Solar Power (CSP) as a technology to produce cost effective hydrogen to be applied as energy carrier in transporttation. Today, CSP technology is neither mature nor deployed on a large scale. However, several recent studies show promising technical and economical progress of this technology, while new CSP installations in Spain and North Africa are currently in construction or have become operational.

Origins of this study are twofold. First, MNP is interested in the assessment of the techno-economic and environmental possibilities of CSP, and more particularly to obtain a second opinion on an available report on CSP (Sargent & Lundy 2003). Secondly, fuel cell vehicles are widely mentioned as a promising technology to achieve sustainable transportation, however, the availability of cost effective and sustainable hydrogen provides formidable barriers to large scale introduction of fuel cell vehicles. CSP may provide an opening to generate hydrogen for future fuel cell vehicles.

This study examines the link between hydrogen production through CSP on the one side, and the use of hydrogen by fuel cell vehicles on the other, by investigating most likely pathways from CSP to future fuel cell vehicles. The time horizon of this study is set on the year 2030. Energy chains are evaluated and considered in respect to its importance to cover a meaningful part of the energy needed in transportation.

Perspectives of CSP

In general it can be said that CSP has promising perspectives to generate a vast amount of sustainable electricity in the future. Experience with field tests of plants developed in the 1980s have been, and are still successful. Currently an upheaval in the interest to set up CSP plants can be observed, leading to further learning and scale effects. Most likely locations for CSP include North Africa (Sahara, Arabia - due to high radiation levels) and Southern Europe (e.g. Spain).

Based on an analysis of available literature and supported by the expertise of partner DLR, the estimates of Sargent and Lundy (2003) concerning future electricity costs from CSP are found realistic. The projections are based on real-life experiences with available CSP technology in the US. The deployment rates of CSP assumed by NREL do not seem unrealistic considering today's attention for CSP technology and the list of planned CSP projects (e.g. in Spain).

Based on these deployment rates, the costs reductions as projected by the NREL study can be characterized as realistic.

Most likely pathways from CSP to Fuel Cell Vehicles

Based on an analysis of individual chain elements, three most likely pathways from CSP to fuel cell vehicle chains have been assessed.

1. Transporting gaseous hydrogen (GH2) per pipeline to Western Europe, and using a hydrogen infrastructure to individual end-users to allow hydrogen home fueling.
2. Transporting liquefied hydrogen (LH2) per ship to Western Europe, and distributing it to refilling stations per tube trailer.
3. Transporting electricity generated by CSP per high voltage DC (HVDC) lines to Western Europe, and distribution to refilling stations to generate hydrogen on site via electrolysis. The HVDC can be a backbone for a sustainable energy infrastructure, in which also other sustainable sources can be plugged into.

The selected chains are expected to be most cost effective, efficient and technically feasible to produce hydrogen from CSP electricity. Given inefficiencies in conversion steps these have been avoided as much as possible. More advanced options for CSP (e.g. thermo-chemical cycles) have not been considered, given the large uncertainties of these options, and the long time frame for further development.

Comparison CSP chains with reference cases

The CSP routes have been evaluated on the following criteria: (i) energy use, (ii) efficiency, (iii) greenhouse gas (GHG) emissions, (iv) land use, (v) costs and more qualitatively on local emissions.

A comparison with two reference scenarios is made to evaluate the CSP chains with conventional fuel chains: (A) a gasoline internal combustion engine (gasoline ICEV) and (B) a plug in hybrid on bio fuels (biofuel-PHEV). The ICEV provides a business as usual scenario, while the bio fuel-PHEV presents a more innovative option to cut back on GHG emissions and maximize the CSP-generated electricity.

In general it can be said that the CSP routes provide an attractive alternative for the ICEV reference case. Improvements of energy efficiency by a factor 1½-2 can be reached on a well-to-wheel basis, particularly by the LH2-route and HVDC-route. GHG emissions of the CSP routes can be reduced with 70 to 95% compared to the ICEV reference. Similarly, although limited data are available, the CSP routes can be expected to reduce local emissions (particularly in the Netherlands due to non-emitting fuel cell vehicles). Only levels of SOx may be higher due to emissions during shipping.

From a cost perspective the LH2 and HVDC routes are most promising relative to GH2. This is largely due to high prices for the homefill installation. However compared to gasoline, cost prices of hydrogen from CSP will be a factor 2,5 to 5 higher (depending on oil price sensitivities). This is largely due to conversion steps required for the CSP routes and relative high prices of CSP electricity compared to conventional fuels. Transport is a relatively small factor (10-20% of the total cost price).

The PHEV route illustrates how storing CSP electricity directly in a battery (in the car) reduces GHG emissions and costs (even compared to the gasoline route) and increases efficiency. Conversion steps are avoided, while this route demonstrates the advantages of electric vehicles over fuel cell vehicles in overall well-to-wheel efficiency.

The only negative point of the bio fuel-PHEV route concerns the required land use. CSP proves to be a technology that requires limited amounts of land, comparable to current oil and gas land use requirements. In comparison, the bio fuel-PHEV requires a factor of 15-20 more land to provide as the CSP routes for the production of bio fuels. Given that CSP does not compete with industrial or agricultural needs for land, CSP is a more promising technology than biomass from a land usage point of view.

Transition evaluation

Chapter 5 describes the transition development of CSP characterized as research and development focus (1970s), set up of demonstrations (1980s), decline in interest (1990s) and renewed interest (2000s). Following the MNP analysis method and using case material of the different periods some conclusions can be drawn concerning CSP.

The descriptions of the transitions of CSP on the one hand and FCVs on the other, illustrate the complexity of transition processes. Three processes are of particular interest. First the cases show how interest in a technology can accelerate, leading to a larger community of stakeholders, increased investments, targeted regulations or supporting programs, increased R&D programs as well as demonstration programs. Second, in the case of CSP also a decline in interest was observed. Third, differences between countries can be observed. Particularly relevant for the Dutch case are the differences between the German and Dutch involvement in CSP.

Regarding the upheaval and decline in interest of CSP, the following factors were found to influence this process:

- High **oil prices** have provided an important context factor for investments in CSP, explaining at least part of the ups and downs of CSP. However, oil prices alone cannot explain the case of CSP.
- **Supporting measures** feed-in tariffs provide a powerful explanation for the current interest in CSP by Spanish organizations. Similarly the North-African projects are largely profiting from attractive subsidy/financing schemes.

- **Demonstrations** have been relevant in providing practical data (data we currently use to justify low cost projections), and provide a proof of principle from a technical and economic point of view. Demonstrators have fueled the visions for investors, industry as well as policy makers.
- **R&D projects** have been important factors to build up further knowledge regarding CSP. Large subsidy schemes in the US and Europe have been instrumental in bringing knowledge forward to further bring CSP closer to commercialization.

The case for FCVs is different from CSP in terms of investments, type of industry involved and political power behind the FCV developments. Important explaining factors for the rise in FCVs include the stringent regulation (California), competition between carmakers and anticipation of high/dynamic oil prices have played a role, although more skeptical views include public relation motives. Nevertheless, the FCV case shows how the industry has become self-propelling with a large number of stakeholders and investors, although large scale commercial projects have been limited so far.

The study ends with a number of implications of CSP potential for the Dutch government. Although CSP is not commercially viable within the borders of the Netherlands, further research could be directed to assess the possible role of CSP in relation to climate policies, development opportunities of developing countries, and industrial activities in CSP in the Netherlands.

Table of contents

1 Introduction

1.1 Background of this study

Great concerns exist on the negative environmental impact and possibly consequences for the future energy supply caused by current use of energy sources and carriers. This issue is also associated to geopolitical stability and the effects of climate change. As part of the solution, renewable energy sources are being developed intensively, such as solar energy (thermal and PV), wind, geothermal, hydro, sea energy in waves, current and thermal gradients.
Being abundantly available, solar energy can play a role as a clean and renewable energy source. Therefore, different technical options are under development to harvest solar energy for modern applications. Encouraged by positive results, significant field tests are ongoing and planned to feed the learning curve towards viable systems.

This study is focused on the feasibility of Concentrating Solar Power (CSP) as a technology to produce cost effective hydrogen to be applied as energy carrier in transportation. Key aspects seem to be the readily available quantities of fuel, and eventually an affordable price per kilometer of transport for the user.
Today, CSP technology is neither mature nor deployed on a large scale yet. However, several recent studies show promising technical and economical developments of this technology. This makes CSP an interesting option for future energy and/or hydrogen supply.

The Milieu- en Natuurplanbureau (MNP)[2] is currently carrying out an evaluation of the transition policy as conducted between 2001 and 2006, with the objective to acquire learning experiences to stimulate system changes on the long term (2040) with significant environmental improvements. As part of the objectives various energy sources and carriers are evaluated which would possibly fit in these objectives. CSP technology is seen as an interesting long term option for sustainable energy supply, while fuel cell vehicles provide a promising application of hydrogen as a sustainable fuel.

The origins of this study are twofold. On the one hand, MNP is interested to assess in more detail the techno-economic and environmental possibilities of CSP. MNP is particularly interested to get a second opinion on the NREL report on CSP (Sargent & Lundy 2003), that sketched cost perspectives for CSP as competitive to conventional energy costs.

[2] English name: Netherlands Environmental Assessment Agency (MNP).

A second angle to this study is the origin of hydrogen for fuel cell vehicles, widely mentioned as a promising technology to achieve sustainable transportation. However, although efficiency of fuel cell technology is relatively high (compared to internal combustion engines), the source and production efficiency of hydrogen is increasingly evaluated more critically. CSP may provide an opening as the fuel of future fuel cell vehicles.

1.2 Scope and objectives

This study provides the link between hydrogen production through CSP on the one side, and the use of hydrogen by fuel cell vehicles on the other, by investigating most likely pathways from CSP to future fuel cell vehicles.

The objectives of this study are threefold:

1. Provision of a second-opinion on the NREL study (2003) concerning the long-term technical, economic and environmental perspectives for solar thermal plants to produce sustainable energy. The evaluation of the cost perspectives takes a central place.
2. Identification of the most likely chains from solar thermal installations (well) to fuel cell vehicles in Western Europe (wheel), and compare these chains with two reference cases on economic and environmental merits.
3. Evaluation of the transition processes of the system option ‘solar thermal plants and fuel cell vehicles'. Special attention will be paid to the policy effects on these transition processes.

The time horizon of this study is set on the year 2030. Energy chains are evaluated and considered in respect to its importance to cover a meaningful part of the energy needed in transportation.

1.3 Approach

Given the various objectives, this study can be divided in two parts, (i) a technical evaluation and (ii) a policy evaluation.

The first part of this study starts with an introduction to solar thermal installations. Furthermore, in chapter 2 an evaluation of the NREL study is made to assess the realistic nature of the cost perspectives given.
Chapter 3 describes the possible chains from solar thermal installations to hydrogen chains. Based on a schematic overview of complete well-to-wheel chain, individual elements of the chain (production, transportation, distribution, utilization and intermediate storage capacities) are separately discussed, using available literature and experts.

The three most realistic chains to produce hydrogen for fuel cell vehicles by means of solar thermal technology are defined, based on technical perspectives, efficiency, costs, safety, and greenhouse gas emissions (GHG).
In chapter 4 the three selected chains are compared to two reference chains. This provides insight in how these chains perform on the different aspects costs, (chain) efficiency and environmental aspects (local emission and GHG emissions).

The second part of this study focuses on the two transition evaluations of both CSP and fuel cell vehicles. First, the transition processes of these technologies are independently assessed with strong emphasis on the development of CSP. Secondly, within the context of this study developments in the field of solar thermal power for fuel cell vehicles are also explicitly assessed.
In order to evaluate the transition processes of both options in a consistent way, we rely on a methodology developed by MNP. This evaluation methodology has a pragmatic approach and facilitates in dealing with the special character of system options like CSP and fuel cell vehicles. Core of the methodology is to record all necessary information to gain insight in the policy effects on the transition process.
The evaluation of CSP will not be restricted to the Netherlands because the solar thermal market definitely is international oriented. Where possible, developments in the Netherlands are made explicit for its relevance for the Dutch transition policy.

2 Perspectives solar thermal plants

2.1 Technology overview

This chapter provides a short overview of the CSP technology, its technical features and its potential use in hydrogen production. The production of hydrogen with CSP is highlighted because this technology combination forms the basis of this study. In 2.3 the NREL study is presented and evaluated.

2.1.1 Energy from the sun

Solar thermal plants use energy from the sun to produce electricity. The quantity of solar radiation that can be harvested is linearly related to the energy intensity of the incoming direct solar radiation. The map provided in Figure 1 indicates measured solar intensities in the Trans Mediterranean region. A reasonable performance of concentrating power plants is given at a solar irradiance of more than 2000 kWh/m2/year. The southern parts of Europe and Northern Africa are most suitable areas to develop solar thermal plants. The direct solar irradiation in the Sahara region can reach values of 2800 kWh/m2/year.

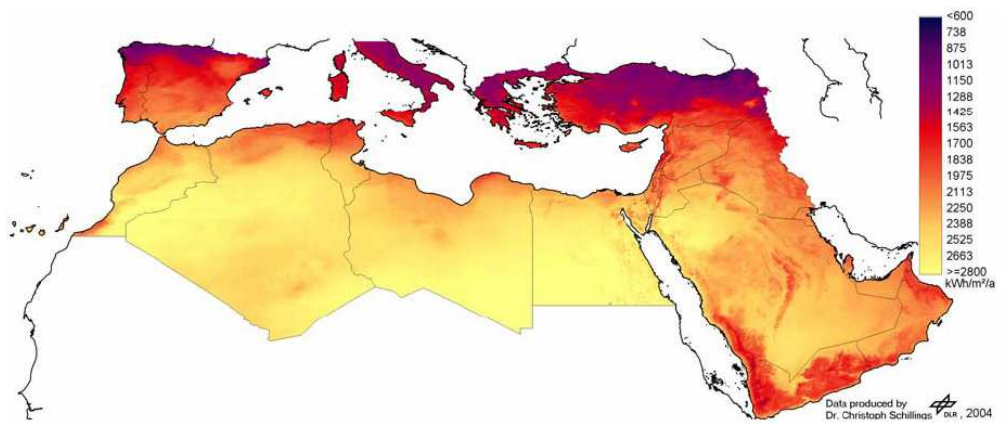


Figure 1: Annual direct normal irradiance in kWh/m2/year. Mapping of the solar energy intensity in Southern Europe and Northern Africa. (Source: Trieb, 2006)

The solar power production potential in the Trans Mediterranean and Europe is depicted in Figure 2. The colors indicate the CSP generating capacity in MWh/km^2. The dark green parts (Sahara, Arabia) refer to about 30 MWh/km^2. The amount of energy that could be generated in the Sahara totals to about 250 GWh/km^2 per year.

This potential can cover the total European energy consumption (about 2500 TWh/y), by a factor >300 times (Kabariti, M. et al., 2003). This makes the northern part of the Sahara and the Arabian region the most suitable for the production of CSP-electricity.

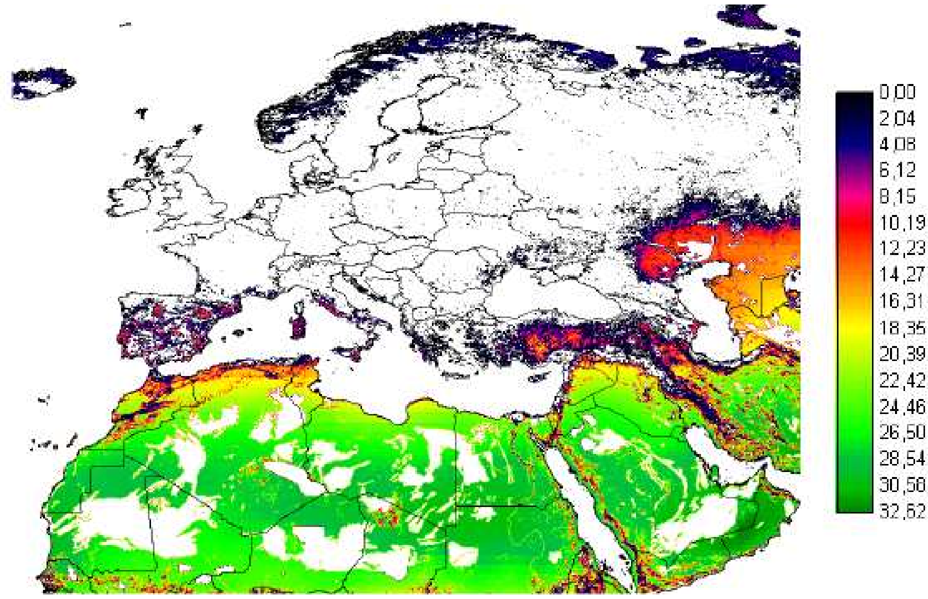


Figure 2: Energy generating potential of CSP in MWh/km2. White zones are excluded for various reasons. The data source has been indicated this data from DLR[3] an ISET[4] (Kabariti, M. et al., 2003).

2.1.2 Basics of CSP technology

The first step in harvesting solar thermal energy is to concentrate the direct solar radiation obtaining a high temperature source for the heat. This is done with the so-called CSP technology. The three most promising CSP types of systems (depicted in Figure 2) are:

- Parabolic Dish
- Power Tower
- Parabolic Trough

[3] DLR: Deutsches Zentrum für Luft und Raumfahrt
[4] ISET: Institut für Energieversorgungstechnik

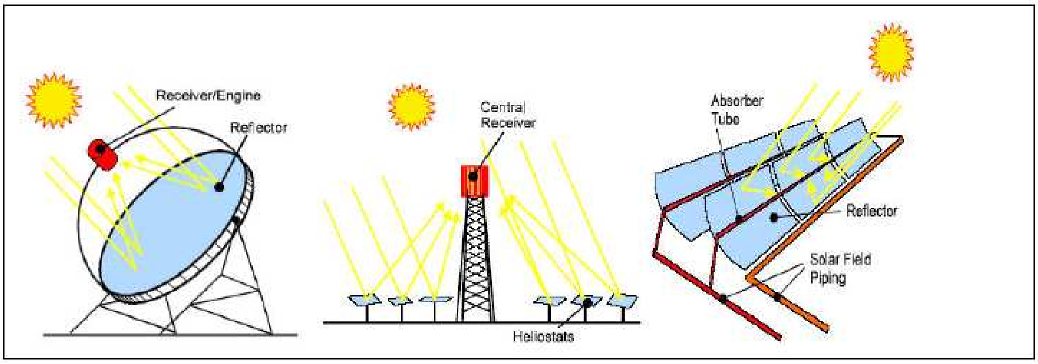


Figure 2: Solar concentrator concepts: Parabolic Dish, Power Tower and Parabolic Trough (see text below). Source: IEA at www.solarPACES.org

The *Parabolic Dish* is continuously oriented to the sun using a tracking system. In this way it effectively concentrates the solar radiation to the receiver of the heat engine that in turn produces the electricity. The individual capacity of the parabolic dishes is up to 50 kW_e. In solar plants these are aligned in superstructures.
The *Parabolic Power Tower* receives its heat from many heliostat mirrors. A liquid in the tower is circulated to a heat exchanger that generates steam. This in turn is used in a conventional steam cycle with a generator coupled to produce the electricity.
The *Parabolic Trough* system consists of collectors that are aligned in the north-south direction. A tracking mechanism ensures the opening of the trough is oriented to collect the maximum yield of direct heat. In a similar way as the Power Tower, the heat is collected in the circulating oil, which in turn produces steam that fuels the steam cycle-generator combination, to generate the electricity. The Parabolic trough concept has a variant with a fragmented structure instead of the curved shape; this is called the *Fresnel* type of solar collector.

2.1.3 The production of electricity from heat

CSP plants use differently shaped mirrors and a different alignment of the subsystem to collect the heat. The heat is accommodated in a circulating liquid medium (e.g., water, synthetic oil, or molten nitrates). In the next step the heat is used to generate electricity by using different types of heat engines-generators. The electricity is produced in rather conventional methods using steam generated by the concentrating heat. Depending on the size of the system these can be Stirling engines or Rankine cycle steam turbine-generator sets.

Some data exist on the efficiency of the solar-to-electricity production, typically in the order of 20 % at peak power[5]. For solar to electric conversion efficiencies, the typical overall efficiencies from table 2-1 can be considered.

[5] The efficiency refers to the quantity of radiation entering the mirror opening.

Table 1: Overview of demonstrated and projected efficiency of parabolic trough and solar tower technology (Source: (Müller-Steinhagen and Trieb (2003, 1 and 2) (d: demonstrated; p: projected)

System	**Peak solar efficiency** Net power / incident beam energy	**Annual solar efficiency** Corrected for averaged capacity factor	**Land use** In m^2 / MWh.year
Parabolic troughs:	21% (d)	10-15% (d) / 17 – 18% (p)	6 - 8
Solar Towers:	20% (d)	8 – 10% (d) / 15 – 25% (p)	8 -12

The demonstrated values are based on long term operational experience for parabolic trough plants or large scale testing experience for solar tower systems. These efficiencies relate to the solar radiation energy IN and electricity OUT. Solar radiation energy is the direct normal radiation as measured by a tracking instrument. The peak efficiency relates to the highest efficiency of the system measured under optimal conditions.

The large-scale field tests results are encouraging. Reduction in hardware cost and operation and maintenance appear positive in the economy of scale. Particularly the experiences with long-term exploitation with the trough systems (some 15 to 20 years) establish understanding and confidence in this technology. This information is of particular interest to predict the performance of future larger systems and in the considerations on investment of future systems.

Figure 3: Picture showing five 30 MW_e units of the solar parabolic trough plants at Kramer Junction, California (source Quaschning and Trieb 2001)

2.1.4 Availability

The amount of electricity that can be produced by a CSP system is directly related to the amount of direct sunlight captured. The availability of the system trough the days and years is a major factor in the economic management of energy supply systems. Not only CSP, but all energy technologies must be able to fulfill the energy demand at any time and any place. A characteristic of the solar resource is that it is not always available according to the demand. This problem of low availability can be solved by thermal storage and/or hybrid operation of the plant (see Figure 4).

In case of hybridization, the practical solution these days is to use natural gas to superheat the system. Actually, the USA systems use some 25% of natural gas, the European systems take 15%. Technically, superheating of the system by natural gas can in fact expand the production hours to the full day (see Figure 4). This approach appears not only successful to increase the availability of the electricity production in standard use, but it is also beneficial to the quality of the electricity. This means additional increased income can be generated by tuning the production to fit better within the electricity market (e.g., optimizing the stability of contracted deliverance and/or flexibility to respond to fluctuating market prices).
At times that there is an overcapacity of heat, the thermal heat is send to a storage tank. This heat can be used to drive the turbine when the solar irradiation stops. Hybrid operation of the plants can be reduced when increased solar thermal storage capacities become available.

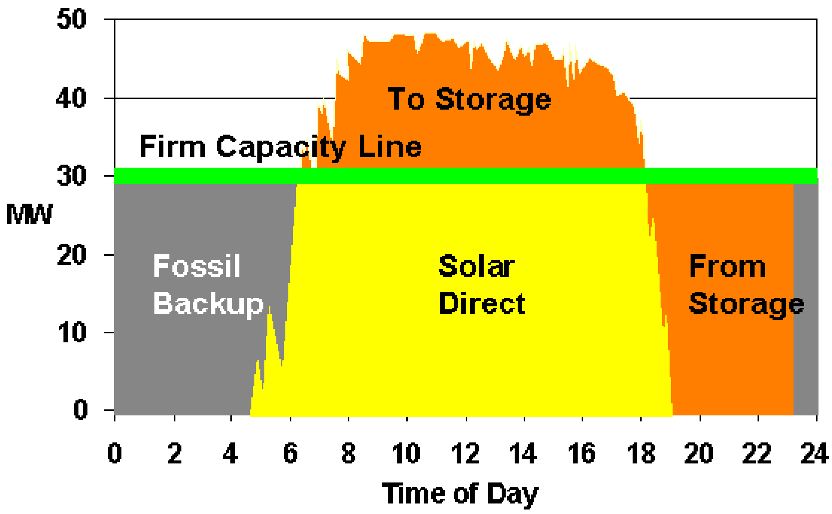


Figure 4: Diagram expressing the energy streams of a daily storage capacity in a natural gas assisted hybrid solar CSP system

2.2 Evaluation NREL report

In 2003, NREL published their report "Assessment of Parabolic Trough and Power Tower Solar Technology Costs and Performance Forecasts". This analysis of parabolic trough and power tower technology cost and performance was conducted by Sargent & Lundy. Especially the suggested perspectives on future electricity costs from solar thermal power are interesting, because it could make the production of hydrogen with solar thermal power combined realistic for use in fuel cell vehicles. In case that hydrogen can be produced in a sustainable and cost effective way by means of solar thermal power this opens up the market for the implementation of fuel cell vehicles.

We limit the NREL study evaluation to an evaluation of the future electricity production costs of CSP and technological progress. A first step is the verification of the cost perspectives as presented by NREL. Secondly, it is decided which cost figures could be used in the comparison of the different 'CSP to fuel cell vehicle' chains.
The evaluation of the NREL study has been carried out in close cooperation with the solar research unit of DLR. They have given a second opinion specifically on the cost perspectives of CSP as presented in the NREL study.

2.2.1 Headlines of the NREL report

Sargent & Lundy's (S&L) analysis of cost-reduction potential of CSP technology covers the period of the next 10 to 20 years. The report examines current trough and tower baseline technologies and includes an assessment of the cost and performance basis of these plants. Future projections are made based on industry projection for technology improvement and plant scale-up to 2020. A cost and performance analysis of these future trough and tower plants is included. The most interesting part within the scope of this project is the assessment of the level of cost reductions and performance improvements that are likely to be achieved according to S&L. The most essential points made by S&L are:

- CSP technology is a proven technology for energy production, however it has not been widely demonstrated as yet (no large scale implementation).
- There is a potential market for CSP technology.
- Significant cost reductions are possible if reasonable deployment of the technology occurs.

In the following section these assumptions are evaluated, partly through own analysis of available references, partly through support of DLR.

2.2.2 State of the art and perspectives

The S&L analysis includes two solar thermal technologies that currently have most potential to achieve a market breakthrough: parabolic trough and power tower. These baseline technologies are the examples of the next plants to be built (NREL, 2003). This section assesses the figures presented by NREL on future electricity costs and technological progress of solar thermal plants.

Electricity costs

The cost of electricity is usually based on the cost of fuel, conversion efficiency, capital costs and the availability of the system. Using solar energy, the fuel cost is zero[6]. Current CSP technology systems that have been realized are within the cost range of USD 0.19/kWh to USD 0.25/kWh (IEA, 2005).

An estimation of future cost developments is given in Figure 5. It shows the tendency of reduced electricity cost and an indication of Advanced Concentrating Solar Power[7]. Commercial solar plants (read: 354 MW SEGS in California) reached leveled energy costs of about 12-15 $cts/kWh through learning experiences. The picture also indicates that solar thermal electricity is likely to compete with conventional electricity for intermediate and peak load power in the near future. On the long term the cost perspectives for CSP electricity in 2030 are estimated at 4 to 5 $cts/kWh.

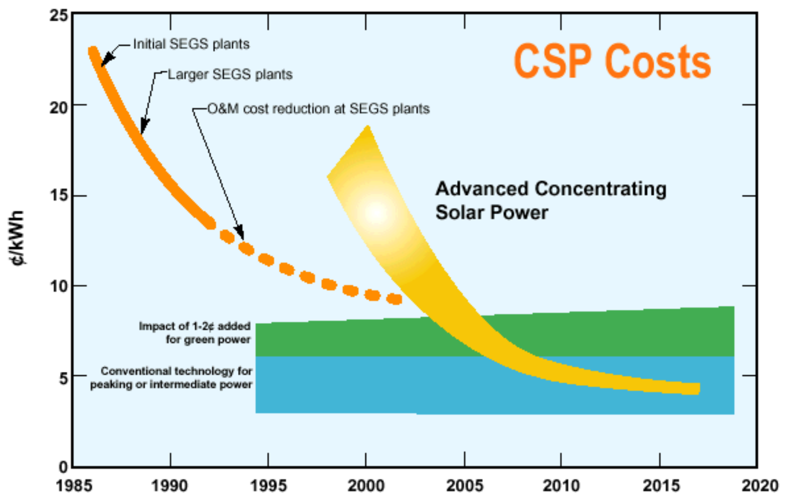


Figure 5: Projected development of the cost of electricity using SEGS[8] (source: www.powerfromthesun.net)

[6] Evidently this is different with natural gas hybrids which have a partial contribution on the actual amount of the natural gas applied.
[7] Advanced Concentrating Solar Power options include advanced thermal chemical cycles and technologies such as PEC, as described in chapter 3.2.
[8] SEGS Solar Electric Generated Station; solar steam generator with either a solar or a natural gas super heater.

As a starting point for their estimates on cost reductions due to volume production, plant scale up and technology improvements, NREL uses cost values from existing plants. At the moment trough technology is further advanced than tower technology. The nine SEGS plants, with a total installed capacity of 354 MWe, provide for 15 to 20 years of operating experience with parabolic trough technology. Investment, operating and maintenance costs of parabolic trough technology are based on long term experience. Current electricity production costs from the last built SEGS plants (SEGS VII-IX) reach levels of 11-14 $ cts/kWh (Müller-Steinhagen and Trieb, 2003).
Operating experience with the power tower technology is limited to the 10 MW Solar I and II prototype plants, which have been operated for several thousands of hours. The tower technology still has to proceed from demonstration to commercial development.

In the coming years there will be a significant increase in installed capacity due to increased demand until 2020 (and probably even after 2020). The NREL study assumes a cumulative deployment of about 2.7 GW_e for parabolic trough plants and 2.6 GW_e for power tower plants in the period 2002-2020. With these deployment rates leveled costs of electricity of parabolic trough will reduce from 10 ct/kWh to 6.2 ct/kWh. These cost figures relate to the SEGS plants in the Mojave Desert with DNI-values of about 2.600 kWh/m^2 and year. Sites in Southern Spain for example have DNI-values of about 2.000-2.100 kWh/m^2, with accordingly less electricity produced and consecutively higher cost per kWh (DLR, 2006). Electricity costs for parabolic trough systems in Spain (Seville) are calculated at 8 ct/kWh (Pitz-Paal et al., 2005).
Power tower costs are expected to reduce from 14 $cts/kWh to 5.5 ct/kWh. If the power tower enters commercial deployment the leveled electricity costs for long term deployment will be less than for trough technology.

S&L include a more technically aggressive low-cost case from the National Laboratories "SunLab". Cost figures indicate a low-bound cost case. Differences in electricity costs are mainly caused by different assumptions on the deployment rates in the period 2002-2020. Cost figures from S&L and SunLab together provide a range within which the costs are expected to decrease. Although we present both cost figures in Table 2 for this study we will rely on the cost figures given by S&L.
The S&L analysis finds that cost reductions are due to volume production, plant scale-up and technological progress (NREL 2003). For parabolic trough technology the largest part of cost reductions will be achieved by technological progress. Solar Tower technology profits most from plant scale-up.

Table 2: Future levelized energy costs (LEC) of solar thermal power (S&L, 2003)

	Current Costs	Sargent & Lundy	Cumulative Deployment	SunLab	Cumulative Deployment
Unit	$cents/kWh	$cents/kWh	GWe	$cents/kWh	GWe
Troughs	10	6.2	2.8	4.3	4.9
Towers	14	5.5	2.6	3.5	8.7

Several other scenarios are available assessing the potential deployment of CSP systems. The Athene Study (DLR/WI/FhG-ISE, 2003) uses a scenario technique that quantifies the world-wide CSP deployment for CSP systems (both trough and tower) trough 2025. It accounts for learning and scaling effects and estimates the overall investments costs and leveled electricity costs. The study estimates that by 2025 over 40 GW of CSP capacity will be installed worldwide. With this capacity installed electricity costs will come down to USD 0.06 ct/kWh, achieved between 2020 and 2025[9]. This means that CSP reaches competitive levels with conventional technologies. These results support the cost prices mentioned by S&L.

2.2.3 Conclusions

The estimates that the NREL study gives on future electricity costs from solar thermal plants are realistic and are based on real-life experiences with available CSP technology in the USA. The cost projections are largely in line with several other cost project studies, and the results of the NREL study are supported by DLR, a leading expert in the field of solar thermal installations. Furthermore, the deployment rates of CSP assumed by NREL do not seem unrealistic considering today's attention for CSP technology and the list of planned CSP projects (see appendix 4). Based on these deployment rates, the costs reductions as projected by the NREL study can be characterized as realistic.

Given the source and analytic tools used by S&L to come to realistic cost projections, their cost figures will be used in further calculations in this report: 10-14 €cent/kWh (2010) to 5,5-6.2€cent/kWh (2030), based on assumed solar irradiation levels of 2.600 kWh/m2/year (North African situation).

[9] Based on a progress ratio of 86% for cumulative installed capacity and 88% for annual energy yield (IEA, 2005).

3 Solar thermal electricity to traction

3.1 Introduction: Identification of chains

In the previous the perspective of solar thermal installations was evaluated. In this chapter the viability of solar thermal energy for generating hydrogen to be used in fuel cell vehicles will be considered.

Cost-effective solar thermal installations need to be located below 40˚ altitude, such as Northern Africa or Southern parts of Europe. Therefore, in case solar thermal energy is to be used to power fuel cell vehicles in Western Europe, one of the main questions is how the energy of the generated electricity in these installations could be transported effect-tively to the Netherlands.

This chapter provides an analysis of possible chains from solar electricity to traction and discusses the different conversion steps in between. The objective is to identify several of the most realistic supply chains and their characteristics. Eventually, an indicative quanti-tative and qualitative evaluation is made of the three most attractive and realistic chains.

Figure 7 depicts a scheme of chain options to be considered. The top line provides an overview of different steps in the chain: from solar thermal production of electrical energy up to utilization by the end-user in transportation. The scheme allows for an analysis of the different chain steps individually, with the objective of identifying weak chain steps. Furthermore, this scheme allows for the assessment of the most likely routes from solar thermal energy to fuel cell traction.

The following section deals with the individual chain elements, solar thermal energy production (3.2), long distance transportation (3.3), distribution to the end-user (3.4), and utilization by the end-user (3.5). In 3.6 an evaluation of the most likely chains is presented, to be compared with two transport reference cases (chapter 4).

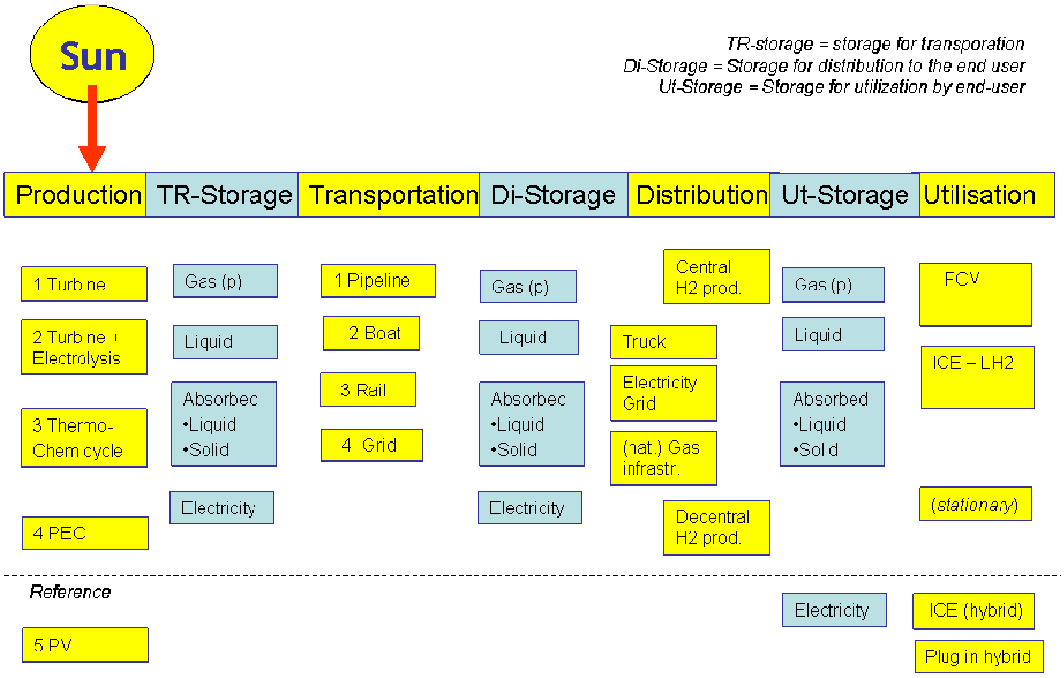


Figure 7: Overview of chain steps from solar thermal energy to traction

3.2 Energy production using solar thermal installations

As discussed in chapter 2, different types of solar thermal systems are available, such as parabolic dish, power tower and parabolic trough. They differ in size, costs and experimenttal experience. The concentrating heat produced can be used to generate different ‘end-products’, mostly electricity, but also direct hydrogen, or chemicals.

Given that this study focuses on using solar thermal installations for the production of hydrogen fuel for fuel cell vehicles, one of the first questions that should be answered is which type of solar thermal installation is most likely to be used in the future. Perspectives of these plants in terms of costs and efficiency should be addressed and also the commercial and technical viability of more advanced options (such as thermo-chemical conversion). The different options are compared on criteria such as cost perspectives, efficiencies and eligibility for large-scale hydrogen production.

3.2.1 Electricity production (turbine)

The most conventional method for applying solar thermal installations is producing electricity using a steam turbine. As mentioned in chapter 2 this method has been applied in a great deal of experiments, on a large scale, and has proved to be a durable system (operation time of over 20 years).

As mentioned in the NREL study (2003) and confirmed by DLR and other studies, costs for electricity production via the through and power tower are in the range of 10 to 14 €ct respectively, and can be expected to reduce to 6,2 and 5,5 $cents by 2020 (Sargent & Lundy, 2003). The indicated cost efficiencies do not only vary with the type of system but also on the solar irradiation level and expected deployment rates.

Solar thermal installations in combination with steam turbines provide the opportunity to generate electricity with relatively low risks, and with a largely available technology.

3.2.2 Solar thermal electricity to hydrogen conversion

The electricity from conventional solar thermal installations can also be used to produce hydrogen, by using the generated electricity to split water into hydrogen and oxygen by electrolysis. The heart of the process is the electrolyser, which is well known from the large-scale industrial production of hydrogen using hydro-electricity (see figure 8). The electrical efficiency of current large scale, commercial electrolysers is in the range of 70 to 74%. Future prospects are indicated up to about 80% (IEA 2005). Theoretically, the electrical efficiency depends on the working temperature and pressure, and on the efficiency loss in the electrolyser (e.g., by internal resistance). This limits the highest practical efficiency until about 85%. Small scale electrolysers have lower practical efficiencies. These days the efficiency of decentralized alkaline electrolysers is about 40 to 50% and could possibly rise to 63% in the future (IEA 2005).

The cost[10] of hydrogen from electricity depends mainly on the electricity price, the efficiency of the electrolyser, the system's capital costs and its operation, and the system's availability. A tendency is observed that, once the technology is developed to maturity, the hydrogen cost is determined for 85% by the electricity cost.

[10] Throughout this report it is assumed that 1 US$ is = € 1 given the focus on long term developments leading to varying conversion factors.

Current costs of hydrogen production can be estimated on € 3,3 per kg[11] (Sargent & Lundy (2003)). This figure will decrease as a result of expected cost reductions and improvements of energy conversion efficiencies. Due to expected cost reductions, energy efficiency improvements (up to 100 %) and developments in new electrolyser types (PEM), future cost projections are estimated on approximately € 2,7 per kg.

Figure 8: Norsk Hydro Alkaline electrolyser, which uses hydro-electricity to produce hydrogen

3.2.2.1 Diffuse solar radiation to hydrogen: Photo voltaic options

The recent upheaval in interest for solar thermal installations has led to several technological options that may be promising for generating hydrogen in the long term. Two of them will be discussed shortly: Photo Electrolytic Conversion (PEC) and high-temperature thermo-chemical production.

PEC is a well known technology that converts solar energy into electricity. Recent developments and implementations are intensive. The cost per produced kWh is expected to decrease in the next 10 to 15 years, to become competitive to other options of conventional electricity generation methods. Photo Voltaic Conversion can be considered as a way to produce hydrogen, this would however require investment in electrolysers (see earlier paragraph), and efficiency losses should be taken into account.

The investment in an electrolyser and efficiency loss is avoided if PEC is applied. This method is a special type of PV, that produces hydrogen directly (so without the electricity step) from diffuse solar radiation. The concept is based on the decomposition of water due to the excess potential of the so-called ‘tandem cells’. It is therefore also suitable for more northern parts of Europe.

[11] The energy content of 1 kg of hydrogen to H_2O is 120 MJ (LHV) or 142 MJ (HHV). The difference, 22 MJ, is the evaporation heat of water.

This technology is in the R&D phase. However, recent results appear quite promising as solar to hydrogen efficiencies have been obtained of about 5%. These efficiencies are expected to rise to about 16% in 2010 (IEA-2005). If developments proceed as expected, PEC may become a better option than PV in producing hydrogen at a reasonable cost in the moderate regions[12] (IEA 2005), e.g. in residential areas. This concept may become of use in decentralized hydrogen production, e.g., to home-fuelers.

3.2.3 Other high-temperature processes to hydrogen: thermo-chemical production

Thermo-chemical cycles involve direct high-temperature conversion of water that net produce hydrogen and oxygen. The high temperatures required can be generated by solar energy.

One of the promising examples of thermo-chemical cycles is the Sulphur-Iodine cycle (SI-cycle). Via a complex set of reactions at different temperatures, hydrogen and oxygen are produced by splitting water. The high-temperature heat used may be as high as at 1100˚C (Schultz, (2003). Depending on the applied temperatures, the efficiencies of the process that have been estimated are quite high (43% at 900˚C). Another promising thermo-chemical cycle using high temperatures generated in CSP include the Zn/ZnO-cycle (Felder and Meier 2005).

Although showing perspective on the long term, thermo-chemical cycles are currently in an early state of development and have, amongst others, intensive corrosion problems to be tackled. The increased attention in recent years for this technology is partly explained by a possible use of thermal energy from high-temperature nuclear reactions. For the CSP case the relative weight of the energy carrier to be transported is likely to limit the large scale use of thermo-chemical cycles[13].

3.2.4 Conclusions

Table 3-1 summarizes the available solar thermal systems for producing energy, either in the form of electricity, hydrogen or absorbed hydrogen form. An estimation of the costs is included as well as an indication of efficiencies.
Efficiencies of CSP generated electricity gives an indication of the most attractive CSP option; but is not taken into account in evaluating Well-to-Wheel efficiencies. It is common practice to consider electricity produced in CSP (or in other sustainable technologies) as primary.

[12] Moderate in terms of type and level of radiation.
[13] Illustrative is the Zn/ZnO cycle: with an atom weight of 65 Zn will produce 2 H-atoms (atom weight: 1). Transportation of 1 H-atom thus requires 'dragging' a weight of 32 times the weight of the hydrogen itself.

Table 3: Evaluation of available solar thermal production technologies

	Output energy carrier	*State of development*	*Efficiency-annual % 2006 (2015)*	*Efficiency H2 20 bar % 2006 (2015)*	*Cost estimation 2010 (2030)*[14]
1 Turbine A Power Tower B Parabolic trough	Electricity	Medium scale experiments CSP	8-10% (15-25%) 10-15% (17-18%)		€ 0,10-0,14/kWh (€ 0,05-0,06/kWh)
2 Turbine + electrolyser A Power Tower B Parabolic trough	Hydrogen	Medium scale experiments CSP. Large scale indust. experience electrolysers	-	6-7,4% (12-20%) 7,4-11,1% (13,6-14,4%)	€ 3,3 / kg H2 (€ 2,7/kg H2)
3 Thermo chemical	Hydrogen	Research, limited and small scale experiments	45-50%	-	Not available
Photo reaction					
4 PEC	Electricity Hydrogen	Research phase, only small scale experiments	-	5% ? (9%?)	Not available
5 PV *(included as a reference)*	Electricity		9,6-13,3% (14,4-16%)	-	€ 0,35-0,40/kWh (€ 0,10-,15/kWh)[15]

3.3 Long-distance energy transport

Once electricity, hydrogen or absorbed materials are produced through solar thermal installations, what are the most suitable ways to transport these products to Western Europe (to be used for fuel cell vehicles)?

In this section the most realistic long-distance transportation options will be discussed, including transportation via pipelines (3.3.1), shipping (3.3.2) and grid (3.3.3). Transportation by railway is not taken into account, although mentioned by Felder and Meier (2005) as an option for transporting absorbed materials (e.g. Zn, Fe, Mn) over large distances. Due to the estimated higher transportation costs, this option will not be elaborated.

[14] Costs for both power tower and parabolic trough
[15] Based on Holland Solar (2005).

The evaluation will be of qualitative nature with assessments of (i) suitability for the different energy carriers (electricity, hydrogen, absorbed), (ii) costs for transportation, (iii) required investments (upfront costs; e.g. in infrastructure), (iv) technical availability/complexity.

3.3.1 Pipeline transport

Like natural gas and industrial gases, hydrogen can be transported through similar pipelines. These days, extensive amounts of hydrogen are transported for industrial use. To this purpose over 1.000 kilometer of hydrogen pipeline is in use in Europe (e.g. in the Netherlands, Belgium, France, Germany), operated by industry gas suppliers like Air Liquide, Air Products and Linde Gas. The industrial experience with this technology could provide a solid basis to future large scale operations and indicates no big hurdles for pipeline transport of hydrogen.

Pipelines are suitable for high pressure hydrogen transport (possibly up to 100 bar). Liquid hydrogen cannot be transported by pipeline given difficulties related to keeping LH2 on low temperatures (-253 degrees Celsius).

The energy content per volume of natural gas is a factor 3,3 higher than hydrogen. This may have consequences for the size of required piping, but has limited effect on costs and efficiency. Calculations by Weindorf et al. (2003) indicate that the required energy for hydrogen transportation over 2.500 kilometer is approximately 18 to 20% (of its energy content). Also compression losses should be taken into account, depending on the pressure requested, e.g., pressurizing from 20 to 100 bar would lead to losses of up to 5%. This investment in pressurization is partially beneficial for the next steps; to even higher pressures or in the liquefaction process.

Currently no infrastructure is available for hydrogen pipelines between energy providing countries (e.g. Spain) and receiving countries (Netherlands). Investments in pipelines are likely to provide major hurdles for large scale implementation. A necessary condition will be the large-scale introduction of fuel cell vehicles and an equivalent rise in demand for hydrogen.

3.3.2 Transport by ships

Shipping is a conventional way of transporting fossil fuels. Energy density of the fuel is of utmost importance. Given that conditions (pressures, temperature) on ships can be influenced relatively well, it is possible to ship large amounts of hydrogen in liquefied state (similar to liquefied natural gas; LNG). This is preferred over gaseous transport given the higher energy density of liquefied hydrogen.

Absorbed compounds

Apart from liquefied hydrogen, hydrogen can also be absorbed in liquids such as methanol (CH_4) or SodiumBoroHydride (NaBH4)[16]. The latter has been demonstrated in a DaimlerChrysler prototype fuel cell vehicle in 2004, given its relatively high hydrogen density. Limitations are in high costs (particularly related to setting up a recycling infrastructure), limited operation in low temperatures and safety issues to be solved. Given these challenges, limited interest of the industry in this energy carrier and limited data, this option is not considered in the remainder of this study.

Liquefied hydrogen (LH2)

In shipping of liquefied hydrogen the following losses will be incurred:

- **Liquefaction losses** The temperature of liquid hydrogen is -253 ˚C (at 1 bar). State of the art large scale liquefaction requires approximately 36 MJ of electrical energy per kg of hydrogen. This translates in losses of 35% of the energy content (LHV[17]). Long term projections indicate that this may be lowered to 21% (IEA 2005, Weindorf et al., 2003). Future liquefaction costs are estimated on approximately 7 €/ GJ (0,84 €/kg) (IEA 2005).
- **Transportation losses** The temperature of liquid hydrogen (-253 ˚C) is much lower than liquid natural gas (-161 °C). As a result, the lower temperature and related amount of boil-off is estimated to be 0,2–0,4 % of the LH2/day (Abe et al., 1998). As a result, the liquefaction penalty shipment cost over 1.000 kilometer has been estimated at € 2 per GJ/H_2 (0,18 €ct/kg) transported (IEA 2005). For a distance of 2.500 kilometer (North Africa to Western Europe) and a ten day trip, this translates into an energy loss of approximately of 2 to 4 %. However, the boil-off hydrogen may be used as an additional fuel for the generator, in which case losses are minimized.
- **Handling losses** Handling of liquefied hydrogen in receiving countries (e.g. Port of Rotterdam) will lead to limited losses in comparison to the energy content of the fuel.

Shipping may provide a good solution for transporting liquefied hydrogen (rather than gaseous hydrogen) to receiving countries, and does not require major initial infrastructure investments.

3.3.3 Electricity grid

The most conventional (and most discussed) method for transporting solar thermal energy to Western European countries is through the existing HV-AC grid. In that way electricity can be transported over long distances. However, its limited free capacity is a barrier to use it without expansions. Moreover, high resistance losses over the required long distances could be in the order of 15%, but might be improved.

[16] $NaBH_4 + 2H_2O \rightarrow NaBO_2 + 4H_2$

[17] Lower heating value

Instead of 'conventional' AC power transmission, it might be more attractive to distribute electricity produced at CSP sites via DC power transmission lines. Table 4 compares properties of both AC and DC power transmission lines at 5000 MW capacity (Trieb, 2006-1), leading to the following observations:

- HV-AC power transmission has considerably higher losses, particularly regarding overhead line losses and sea cable losses.
- With up to 60% per 100km, sea cable losses are very significant for HV-AC lines (versus less than 1% for HV-DC losses). Given that sea cables are likely to be used in case CSP is located in Northern Africa (most likely via Marocco/Spain), sea cable losses are relevant to consider in the evaluation of high voltage electricity transport to Western Europe.
- HV-DC infrastructure is more expensive than HV-AC regarding terminal costs, but this is compensated by lower overhead line costs and sea cables costs.

Table 4: Comparison of AC and DC long distance transmission lines and its related power losses (Trieb 2006-1)

Parameter	Unit	HVAC		HVDC	
Operation Voltage	**kV**	**750**	**1150**	**± 600**	**± 800**
overhead line losses	%/1000 km	8%	6%	5%	2.5%
sea cable losses	%/100 km	60%	50%	0.33%	0.25%
terminal losses	%/station	0.2%	0.2%	0.7%	0.6%
overhead line cost	M€/1000 km	400 - 750	1000	400 - 450	250 - 300
sea cable cost	M€/1000 km	3200	5900	2500	1800
terminal cost	M€/station	80	80	250 - 350	250 - 350

In conclusion, the HVDC lines and cables, preferably at 800 V are most cost effective, compared to the various AC cables. From an efficiency point of view a more favorable option would be to work with a HVDC-grid. Assuming a distance of 2.500 kilometer, estimated efficiency losses for HVDC are approximately 6% (with approximately 15% for HVAC power lines). Transportation costs to transport the electricity to Europe via HVDC lines have been estimated on €0.01/kWh (Trieb, 2006-1)

A HVDC infrastructure from South to North can in time become part of a future pan-European backbone also connecting east to west as to improve the reliability of the total energy infrastructure by absorbing electricity from various renewable energy sources; in and around the EU (see figure 9).

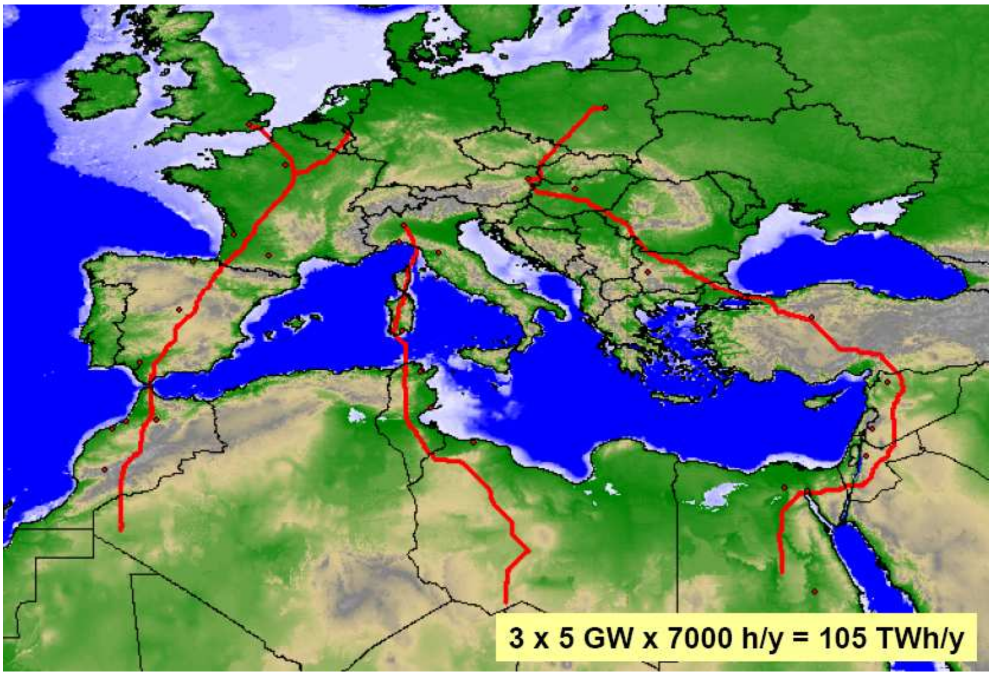


Figure 9: Trans-Mediterranean Interconnection for CSP, Trieb (2006-2)

3.3.4 Conclusions

All three transportation options have their particular advantages, leading to different options for distributing energy produced in solar thermal installations to receiving countries in Western Europe (overview in table 5).

Pipelines are more suitable for transport of gaseous hydrogen (low costs, limited efficiency losses), and are likely to be used in large-scale applications given high upfront investments costs.
Ship transport is likely to be used for (energy dense) LH2, given available infrastructure and limited complexity. Losses and higher transportation costs form the main obstacles.
Lastly, using the grid (particularly High Voltage DC) has particular flexibility advantages for the receiver and limited efficiency losses. An obstacle of grid transport is that there is no unlimited free capacity and investments in additional capacity are needed.

Table 5: Qualitative overview and evaluation of long-distance energy transportation options

	Suitability for energy carriers	Variable Costs (for transport)	Investment costs	Efficiency losses in transport	Complexity
1 Pipeline	GH2	Low	High	Low	Moderate
2 Shipping	LH2	Low	Low	Low	Moderate
	Absorbed compounds	High	Unclear	Low	Low
3 Grid					
- HVAC	Electricity AC	Low/moderate	Moderate/high	Moderate	Low
- HVDC	Electricity DC	Low	High	Low	Moderate

3.4 Distribution to the end-user

Once the energy carriers arrive at the receiving country there are different ways to arrange distribution to the end-user (e.g. the driver of a fuel cell vehicle). Distribution is the connecting step between the long-distance energy supply and demand for automotive fuels (hydrogen).

The conventional way for fuel distribution is by truck or pipeline to filling stations. Although this mode of refueling is likely to remain a major factor in the future, solar thermal power provides alternative refueling opportunities. Particularly routes of (i) decentralized hydrogen production, and (ii) decentralized refueling opportunities may provide attractive opportunities (see figure 10 for an overview).

Different distribution modes of the available energy carriers are possible, including (i) pipelines, (ii) truck transport and (iii) grid. The options will be discussed briefly, and evaluated on (i) cost perspectives, (ii) technical complexity, (iii) infrastructure availability, (iv) and potential value for end-users.

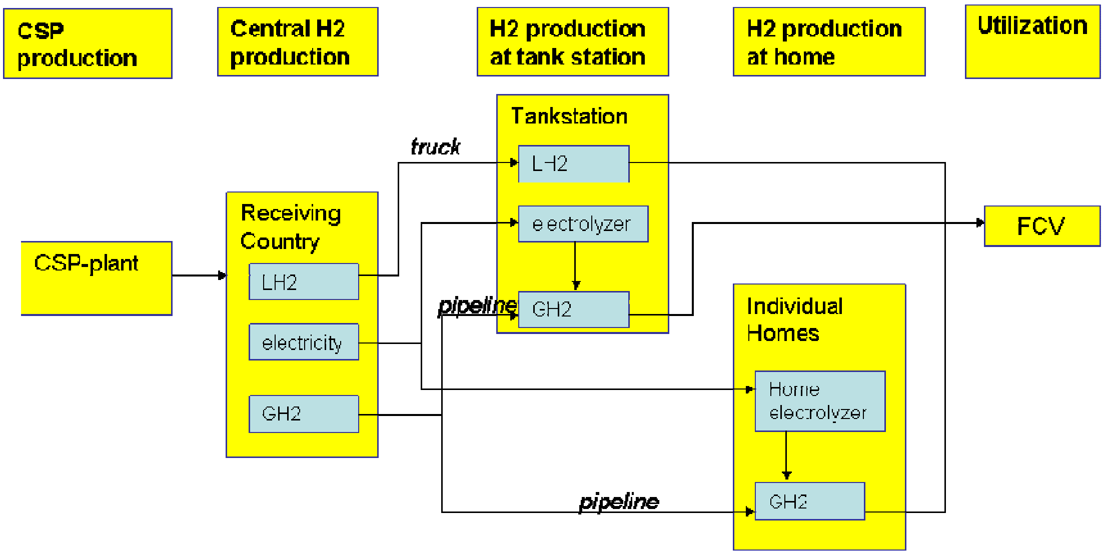


Figure 10: Distribution routes of energy carriers to end-users

3.4.1 Pipeline

Transport via pipelines is an attractive option to deliver (mostly gaseous) hydrogen to the end-user. This can be done on the level of tank stations as well as on individual homes level. The more decentralized the hydrogen delivery is arranged, the higher the investment costs for setting up a hydrogen infrastructure.

The Netherlands is equipped with an extensive infrastructure for natural gas. Although the perspectives of using this network for future distribution of hydrogen are discussed (e.g. in NaturalHy[18]), limitations lie in capacity of the current net (natural gas has an energy density of a factor 4 higher than hydrogen), while dedicated pipelines are required (e.g. materials that reduce leakages and corrosion).

On the long term a dedicated hydrogen infrastructure is likely to be developed, leading to high initial investment costs. In the medium term hydrogen may be distributed in a mixture with natural gas ('hythane') with up to 10% hydrogen without leading to capacity problems. A great deal of research is currently focused on developing membranes to separate hydrogen from Hythane streams, so that the hydrogen can be used for CSP or transport applications with fuel cells. Nevertheless, this option should be seen as a transition step to a dedicated hydrogen infrastructure.

The option of delivering hydrogen to refilling stations may be an attractive option, for instance in high pressure piping (e.g. 800 bar). This would allow for fast refilling of fuel cell vehicles with pressure tanks of 700bar as likely standards in the future (100bar over pressure provides opportunities for fast refilling).

[18] www.naturalhy.net. This EU funded program with more than 20 European stakeholders related to gas, hydrogen and fuel cells is studying the opportunities for developing a hydrogen infrastructure, by phasing in hydrogen percentage-wise in current natural gas stream (up to 5-10%).

3.4.2 Truck transport

Liquid Hydrogen

Similar to conventional distribution, trucks can provide refilling stations with gaseous and liquefied hydrogen, against slightly higher costs and energy losses (compared to pipelines). A 40 ton truck can transport some 3.500 kg of liquid hydrogen. Over a 1.000 kilometer (round)trip approximately 2-3% energy losses are incurred.

Absorbed compounds

Absorbed compounds may also be distributed, and even be used as a fuel (to be refilled). This is illustrated by DaimlerChrysler's fuel cell prototype in which $NaBH_4$ is demonstrated as a fuel. Similarly Metal-Oxide-compounds could be imagined.

The major hurdle for these 'fuels' is the relative weight. The amount of hydrogen relative to the weight of the compound itself is unfavorable and will unlikely provide an attractive option for mobility in the long term. Apart from the limited energy density, the infrastructure requires significant changes. For an operational system a complete logistic system of recycling and supplying the liquid or solid energy carriers needs to be set up.

Trucks versus pipeline

The diagram below (Figure 11) provides insight in specific optimum operational regimes for comparing CH2 and LH2 eligibility for distribution (Ogden and Yang, 2005). It indicates the limited competitiveness of trucked, pressurized hydrogen. Trucked liquid hydrogen is economically interesting for longer distances and a medium to high range of transported amounts. Pipeline hydrogen is interesting for small to large amounts of hydrogen up to the longest distance shown (over 500 kilometer).

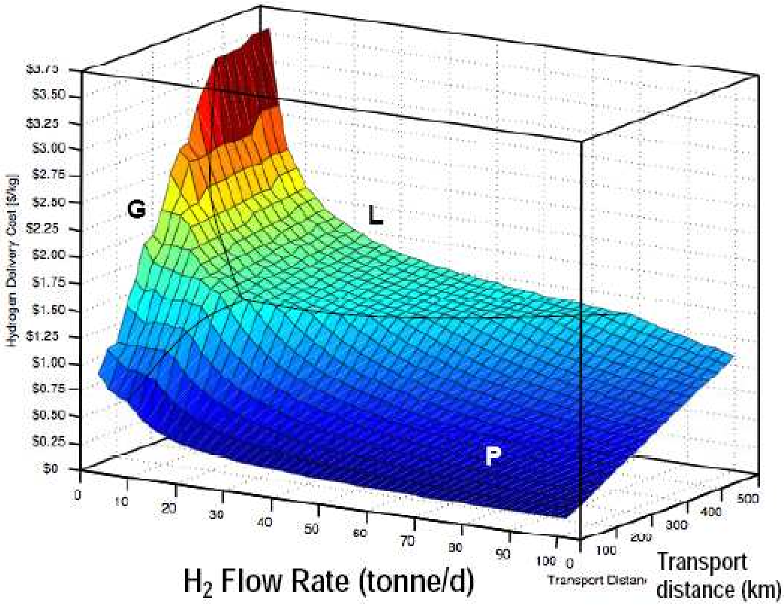


Figure 11: Levelized hydrogen cost of transmission ($/kg) as a function of hydrogen flow-rate (tones/day) for three delivery methods: compressed gas, delivery by truck (G), liquid hydrogen truck delivered (L), and compressed gas by pipeline (P). (Ogden and Yang, 2005)

3.4.3 Electricity for on site hydrogen production

In case 'electricity' is the preferred long-distance energy carrier, hydrogen can be either produced centrally with industrial electrolysers (e.g. Port of Rotterdam, or other major industrial zones) or at a decentralized level with small-scale electrolysers. The latter can be carried out on the level of households or at the level of refilling stations. Similarly, it is possible to deliver electricity to filling stations that produce hydrogen on location, thereby reducing distribution costs and losses.

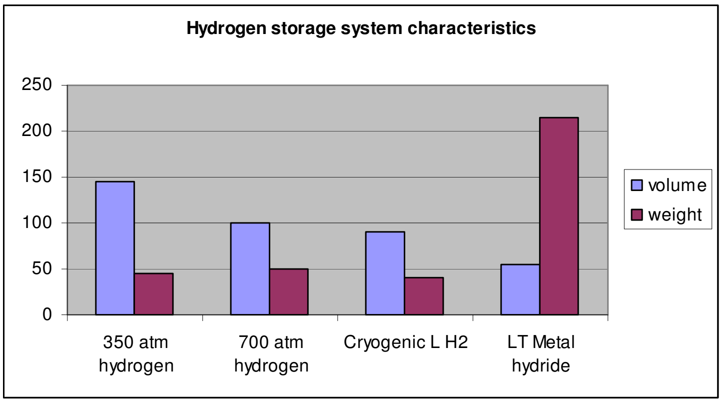
Hydrogen production on household level provides an illustration of a decentralized energy infrastructure usually mentioned by supporters of a hydrogen economy (Rifkin 2002), with self-sufficiency and potentially lower costs as major drivers. Limitations lie in efficiency losses in small-scale electrolysis (compared to industrial scale) and losses in compression. Small-scale electrolysers are currently available, but these are less efficient than industrial scale electrolysers (40-50% and 74 % respectively). However, hydrogen distribution (and related efficiency losses) from centralized production units to refilling stations is circumvented.

Hydrogen production units for refilling stations have similar advantages (low distribution losses and costs) and disadvantages (less efficient electrolysis).

3.5 Utilization

In this project we are assuming an extensive use of fuel cell vehicles. In the end, it is the end user who decides upon what type of car to drive. In this chapter it is assessed how different potential hydrogen fuels compare from the viewpoint of the consumer.

- **Liquefied hydrogen (LH2)** LH2 is more energy dense than GH2, and will therefore provide more range for fuel cell vehicles. However, long term storage of LH2 leads to losses, given that over time hydrogen needs to be boiled off in order to maintain the low temperatures. Currently BMW and Ford are studying LH2 (for ICE purposes). Other manufacturers favor GH2 for reasons of reduced complexity and losses.
- **Compressed hydrogen (GH2)** A great deal of research is currently focused on developing high pressure storage tanks for hydrogen. Systems of up to 1000 bar are under development. Several 35 bar systems currently have certification, while 700 bar is a likely candidate to become standardized in the coming years.
- **Hydrids** The major part of funding on hydrogen storage is spent on hydrids, both solid and liquid. Results are promising however breakthroughs are required to make hydrid storage systems a feasible and commercial alternative.



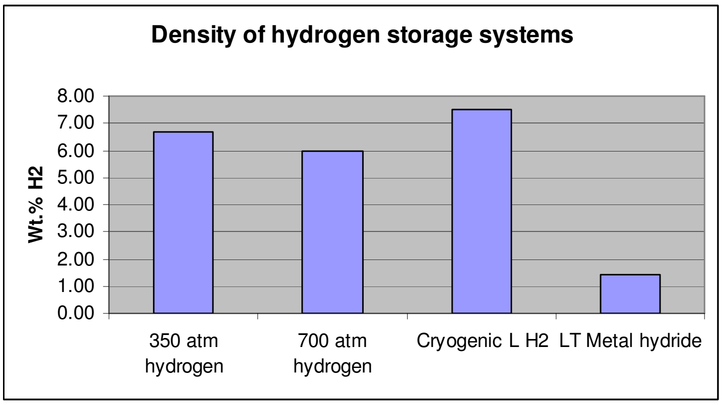


Figure 12 and Figure 13: Comparison of hydrogen storage system volumes and weights (indicative values from Niedzwiecki, 2001)

3.6 Evaluation Solar-traction chains

Based on the provided analysis of the individual elements in the complete supply chain, the most suitable and realistic chains can be identified. Figure 14 sketches three realistic routes from solar thermal to hydrogen usage for fuel cell vehicles. These will be described shortly, and will provide for the reference case in chapter 4.

The main arguments for selecting these chains include the following.

- **Efficiency** Routes with limited conversion steps, associated investments and efficiency losses in the complete chain have been selected. One consequence is that conversion steps (e.g. gaseous liquefied gaseous) are limited as much as possible.
- **Technical perspectives** Thermo-chemical cycles are currently researched, but have not been demonstrated on a large scale. This leads to uncertainties in costs, efficiencies and technical viability, a reason not to take them along in the following chapter.
- **Economic perspectives** Although costs for the different options are hard to assess based on the current state of knowledge, literature does provide indications of technological routes with more perspectives than others.
- **Innovativeness** Particularly on the utilization side it is proposed to explore opportunities for decentralized H_2 production, in order to explore completely different refueling infrastructures.

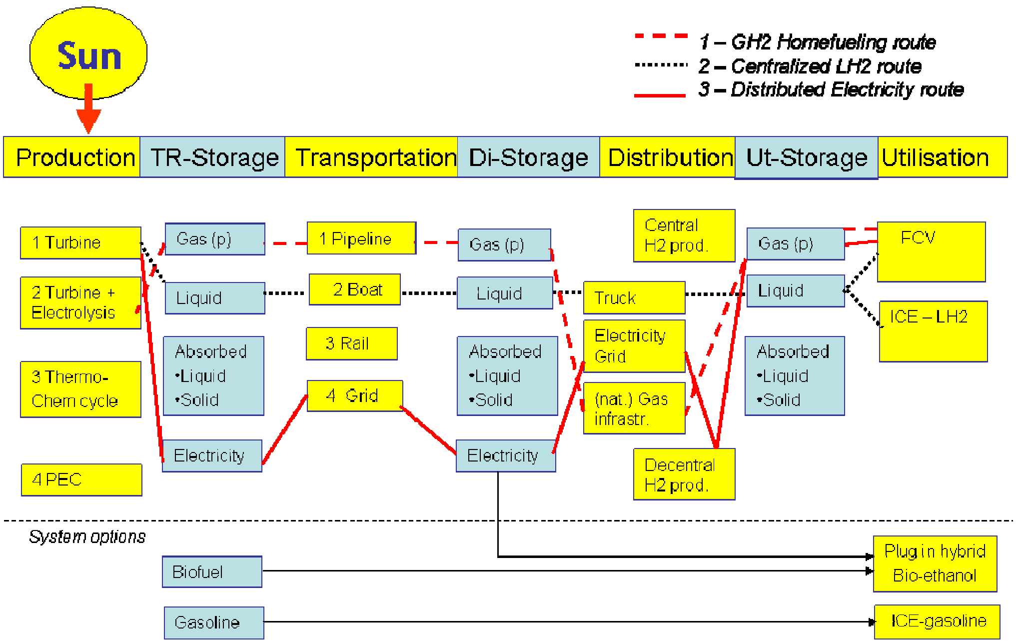


Figure 14: Overview of proposed solar thermal to traction chains TR-storage = storage for transportation; Di-Storage = Storage for distribution to the end user, Ut-Storage = Storage for utilization by end-user

3.6.1 GH2 Homefueling route

The 'Gaseous route' sketches a scenario in which hydrogen is produced centrally at the large-scale CSP-location by using industrial scale electrolysers. Assuming mass-market of fuel cell vehicles in Western Europe, the scenario envisages investments in hydrogen long-distance pipelines allowing low-cost and efficient transportation of hydrogen to receiving countries.

Distribution to the consumer is arranged by distributed pipelines. As mentioned, capacity limitations and material sensitivity of current pipelines will require adjustment of the current infrastructure to make hydrogen available on household level in 2030. As a transition step it is assumed that hydrogen is blended in percentages up to 10-20% to natural gas, and separated on household level with membranes allowing home fueling of hydrogen on the longer term. In the meantime it is assumed that at new building sites infrastructure is developed in anticipation of a hydrogen infrastructure.

Determining characteristics of this scenario include low cost transportation, high investment costs (pipelines) and distributed fueling opportunities (home fueling).

3.6.2 Centralized LH2 Route

Determining characteristic of the LH2 route is the focus on high-density hydrogen usage (required in cars and for long-distance transportation). The route anticipates on a slower transition towards a mass-market for fuel cell vehicles, leading to lower initial investments (versus pipeline development) against higher variable costs (shipping).

Losses in transportation, distribution and utilization are taken for granted, although its is presupposed that significant savings can be made in hydrogen losses during transportation and distribution, for instance by using boil-off hydrogen for fueling ship engines.

Liquid hydrogen is produced on location and is shipped in large-volume vessels. In the Port of Rotterdam facilities for storage, handling and distribution to refilling stations are developed. Liquid hydrogen is transported to existing filling stations by truck, where end-users can refuel their fuel cell vehicles in a 'conventional' way.

3.6.3 Distributed Electricity Route

The electricity based route can be characterized as the most flexible for the energy system of the receiving country, and sketches a scenario in which hydrogen production takes place at the level of filling stations via medium sized electrolysers.

Electricity produced by CSP installations is transported by High Voltage DC gridlines (800V), assuming that efficiency and grid-stability arguments will drive investments in a European DC network. The receiving country distributes the electricity to filling stations via a dedicated low voltage DC net[19].

The Distributed Electricity route diminishes the need for long distance transportation (via ships or pipelines) as well as distribution requirements (trucks or pipelines). Limitations lie in lower efficiencies of (sub-industrial) electrolysers.

3.6.4 Conclusions CSP to Hydrogen chains

This chapter has analyzed the possible routes from CSP generated energy to hydrogen fuel for fuel cell vehicles. Figure 14 provides an overview of the three routes that will be evaluated regarding costs and environmental performance vis-à-vis two reference cases (bio fuel-hybrid and gasoline).

[19] It is assumed that low voltage DC networks can be set up. More research is however required to assess feasibility. A complete DC net would circumvent conversion steps from DC-AC and AC back to DC, given that electrolysers use DC power.

4 Evaluations of selected chains

4.1 Introduction

Chapter 3 provided an overview of three promising chains from well (CSP) to wheel (fuel cell vehicles). This chapter provides an analysis of how these three scenarios perform with respect to (i) energy efficiency, (ii) energy usage, (iii) CO_2 emissions, (iv) land use and (iv) costs. A more qualitative assessment is made of local emissions (NOx).

The objective of this chapter is to assess the environmental performance of the three different CSP routes vis-à-vis two reference cases, namely (i) the Gasoline ICEV Internal Combustion Engine Vehicle (ICEV), and (ii) the Bio fuel Plug in Hybrid Fueled by Bio fuel (PHEV).

The timeframe of this assessment is 2030 which is a realistic for fuel cell vehicles to reach a significant share of the market (L-B Systemtechnik, 2006). In order to give indications on growth potential of several routes, also an estimation of 2010 values is provided.

4.2 Methodological aspects

A well-to-wheel approach is taken to analyze the environmental and economic performance of the different routes.

4.2.1 Tank-to-wheel analysis

Several studies have looked into future propulsion-fuel combinations (Weiss et al 2001, General Motors 2002, CONCAWE 2006[20]). They differ in the combinations evaluated, the criteria evaluated on (efficiency, GHG emissions, local emissions) and time frame. CONCAWE is generally acknowledged as a reliable source of future propulsion-fuel data. Given that the study also has a stronger European car industry focus, CONCAWE is largely used as a data source.

[20] The CONCAWE's study on fuel-powertrain combinations provides an analysis of well-to-wheel energy use and greenhouse gases (GHG). The study is jointly carried out by CONCAWE, EUCAR and JRC (Joint Research Centre). The study has been set up with data provided by the automotive industry and has been supported by a large variety of stakeholders in the automotive and oil industry.

In the assessment the most widespread European segment of passenger vehicles was used as a platform[21]: a compact five-seater sedan (Volkswagen Golf segment). Assessments in CONCAWE are made for the two periods, 2002 (based on currently available information) and 2010+ (including data of expected technological improvements currently in development). Given that the study for MNP is focused on 2030, some adjustments have been made to the CONCAWE data.

- It is assumed that the 2010+ data of CONCAWE represent the state of technology of vehicles in model year 2010. Widespread penetration of this technology is estimated to take ten years, and is likely adopted by a large share of the market by 2020.
- Percentage wise improvements are taken into account to include efficiency improvements for vehicles in the model year 2020. The percentage is based on the improvement ratio between 2002 versus 2010, as estimated by CONCAWE: 10% for both gasoline ICEVs as well as PHEVs.

4.2.2 Evaluation criteria

In the well-to-wheels the different routes are evaluated on the following criteria.

- **Efficiency** Well-to-tank efficiencies are considered to compare CSP routes with each other. Well-to-wheels efficiency is required to evaluate CSP routes compared to the reference cases.
- **Energy** An overall assessment of the energy required per unit distance covered (MJ/100km). Note that in this study, electricity generated from CSP is considered as primary energy source.
- **GHG** An assessment was made of greenhouse gases per unit distance covered (gr CO_2eq/km). Apart from CO_2 emissions, also N2O (as a result of fertilizer usage on farmlands) is taken into account in the CONCAWE study[22].
- **Land use** An indication of land use required in case the respective technologies (mainly fuel cell vehicles and PHEV) reach a market penetration of 20% in the Dutch market.
- **Costs** A cost estimate associated with each pathway and the resulting costs of fuel substitution.

[21] Key to the CONCAWE methodology was the requirement for all configurations to comply with a set of minimum performance criteria relevant to European customers while retaining similar characteristics of comfort, driveability and interior space.

[22] N_2O has a very powerful greenhouse effect (300 times that of CO_2), even relatively small emissions can have a significant impact on the overall GHG balance. Particularly its use as fertilizer for the production of feedstock for bio fuels has proven to have significant impact.

Concerning efficiency, although principally high levels of energy efficiency throughout the chain are favorable, for sustainable energy *efficiency* itself is a less prominent evaluation criterion, given the 'unlimited' availability of sustainable energy sources. However, low chain efficiencies translate in higher land usage, high CO_2 levels, and ultimately higher fuel costs for consumers. The latter consequence of lower efficiencies is likely to be higher barriers to large scale introduction of sustainable energy sources.

4.3 Assumptions of analyzed chains

The most important assumptions for the well-to-wheels analysis for the CSP routes and the reference cases are given below.

4.3.1 Three CSP routes - Assumptions

Assumptions concerning the fuel cell vehicle include:

- Efficiency of fuel cell technology is assumed to be 50%. This relative high percentage can be achieved by adding large battery capacity (hybrid FCV) allowing break energy to be recovered, and achieving higher energy efficiencies on the fuel cell (CONCAWE 2006).
- Energy use for fuel cell vehicles is assumed to be 84MJ/100km (0,70 kg H2/100km) in 2010, and 75MJ/100km in 2030 (CONCAWE 2006).
- The CONCAWE study (2006) assumes similar energy requirements for LH2 and GH2 per distance traveled: the relative higher weight of GH2-storage is compensated by vaporization of LH2 prior to use, and losses in long term storage (boil-off).
- Storage systems of 700 bar storage systems are assumed.
- Cost figures of Sargent & Lundy for CSP electricity production are used: 12 €cent/kWh (2010) to 6€cent/kWh (2030).

4.3.2 Reference A: Gasoline ICEV

It is generally acknowledged that ICE-based vehicles will remain a dominant propulsion technology in the coming decades (CONCAWE 2006; Hyways 2006). This reference thus serves as a 'business as usual', taking into account percentage wise improvements to the internal combustion engine. An exemplary optimization for the ICE assumed in the CONCAWE study is the downsizing of the motor (1,3 liter instead of 1,6 liter engine).

Given the current dominance of gasoline on the EU market, gasoline is chosen over diesel. However, the results of the comparison of gasoline versus the CSP routes are not likely to differ significantly compared to diesel, and thus the results of this study can be largely generalized to diesel.

4.3.3 Reference B: PHEV-bio fuels

The second reference of the PHEV includes more innovative aspects. Rather than being a widely discussed option in the industry (for instance plug-in hybrids are not mentioned in the CONCAWE study[23]), the PHEV may provide attractive synergy potential with CSP.

Central characteristics of PHEVs include (i) a relative large battery capacity (allowing for 40 kilometers+ driving electrically), (ii) an electric motor, and (iii) the ability to charge the batteries via the grid ('plug-in'). Particularly the last characteristic has synergy effects with CSP, given that the PHEV may be charged with electricity generated by CSP and transported to Europe by high voltage power lines.

In effect, the PHEV is largely an electric vehicle that also has an ICE used as a range extender. In this reference case the PHEV is fueled by bio fuels, in order to further investigate the improvement potential regarding GHG emissions.

Relevant assumptions regarding the PHEV include the following.

- The gasoline ICEV is assumed to require 209MJ/100km (tank-to-wheel) in 2010; and 188 MJ/100km in 2030.
- The PHEV is fueled by (bio)ethanol based on sugarcane (feedstock)[24].
- The batteries add significant weight to the car. As a compensation a 10% loss of efficiency is assumed. This is conform values used by CONCAWE to assess influence of battery weight in current hybrids[25].
- It is assumed that 50% of annual distance traveled is covered by the electric motor of the PHEV (with electricity generated by CSP), while the ICE (on bio fuels) powers the remaining 50% of distance traveled.
- As a result the energy requirement for the PHEV is 138 MJ/100km (tank-to-wheel) in 2010, 115 MJ/100km of which is based on bio fuels; 23 MJ/100km of which is based on the electric motor. A reduction to 126 MJ/100km in 2030 is assumed.
- The difference in efficiency (tank-to-wheel) between the electric motor and the internal combustion engine explains why the electric traction requires five times less to travel the same distance.

---

[23] Although automotive OEMs currently do not have (official) PHEV development programs, several institutes (University of Davis, NREL) and several carmakers (Toyota, DaimlerChrysler) have demonstrated some activity in PHEVs. Given the current rise in sales in hybrid vehicles and developments in battery technology (e.g. LithiumIon) a PHEV-concept is not unrealistic on a period of 25 years.

[24] Environmental and economic data are derived from a study currently carried out Hamelinck et al (2006 expected) for the MNP, in which well-to-wheel evaluations are made with respect 12 biofuel chains.

[25] The CONCAWE study assumes that 2010+ hybrids have the capacity to drive 20 km on batteries as a zero emission vehicle – in this study a 40km is assumed to cover a majority of commuter drives.

4.4 Evaluation of chains

4.4.1 Efficiency

First the results of the well-to-tank are made to provide an indication how efficiencies differ between the different CSP-routes in the generation and distribution of fuel to the end-user. A well-to-wheels analysis complements the analysis to get an overview of the overall chain efficiency.

Well-to-tank efficiencies

With regard to the efficiencies of the different routes on a well-to-tank basis the LH2 HVDC route (61% efficiency) and LH2 route (58% efficiency) are most efficient from a well-to-tank basis, compared to 51% for the GH2 home fueling route in 2030 (see figure 15). An overview of losses is given in figure 16 (an overview of the chains is presented in appendix 3 using *Sankey diagrams*).

- The largest inefficiencies in the **GH2 home fueling route** lie in (i) electrolyzing CSP electricity to hydrogen at the CSP location (20% losses), (ii) pipeline losses (12-16%) and (ii) compression losses at the home fueler (assumed 25%).
- In the **LH2 route** losses are incurred as a result of electrolysis (20% losses), liquefaction inefficiencies (22-35% losses in 2030 and 2010 respectively). Losses in shipping are relatively low (2-3% - fuel usage); it is assumed that hydrogen losses can be used for ship propulsion. The LH2 is expected to have large improvement potential with regard to more efficient liquefaction techniques, which explains the relative strong progress between 2010 and 2030 in this route.
- The **HVDC route** has advantages in relatively efficient long distance transport-tation of electricity (8-12% losses). The majority of losses are accounted for by decentralized electrolysis on refilling station level (30-35%).

Also in figure 15 the well-to-tank efficiency of current fuels (**gasoline**) is shown. Given that no conversion steps are required (e.g. liquefaction, electrolysis, compression), the only losses relate to production, which are generally low for fossil fuels (10% maximum). The overall well-to-tank efficiency of the **PHEV route** (65-70%) is lower than gasoline route given inefficiencies in the production of bio fuels as well as the contribution of losses of CSP-generated electricity used to charge the batteries in the PHEV.

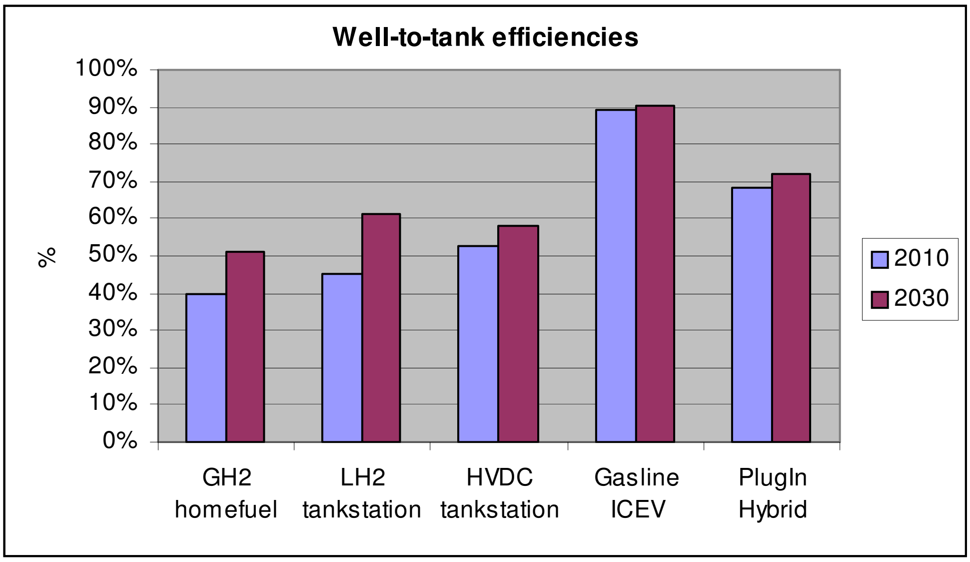


Figure 15: **Well-to-tank** efficiencies

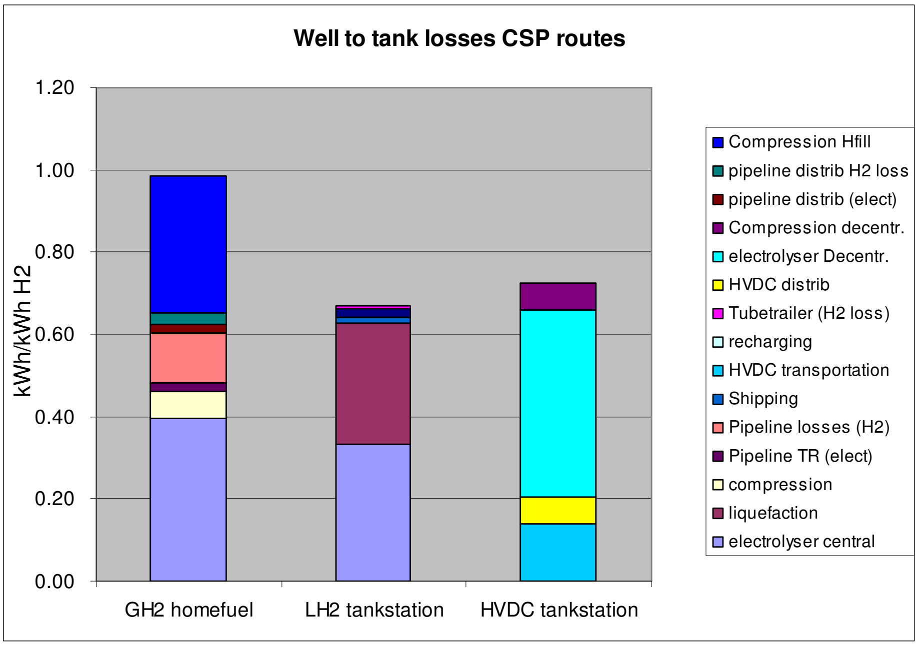


Figure 16: Breakdown of efficiency of CSP routes in 2030

Well-to-wheels efficiency

Figure 17 shows the well-to-wheel efficiency of the different routes with CSP and the reference cases. In comparison, the well-to-tank analysis the figure shows how the efficiency of the fuel cell compared to the ICE compensates lower well-to-tank efficiencies. Efficiencies of the fuel cell are assumed to be a factor 2.5 higher than the internal combustion engine, which is in line with current achievements in demonstrators.

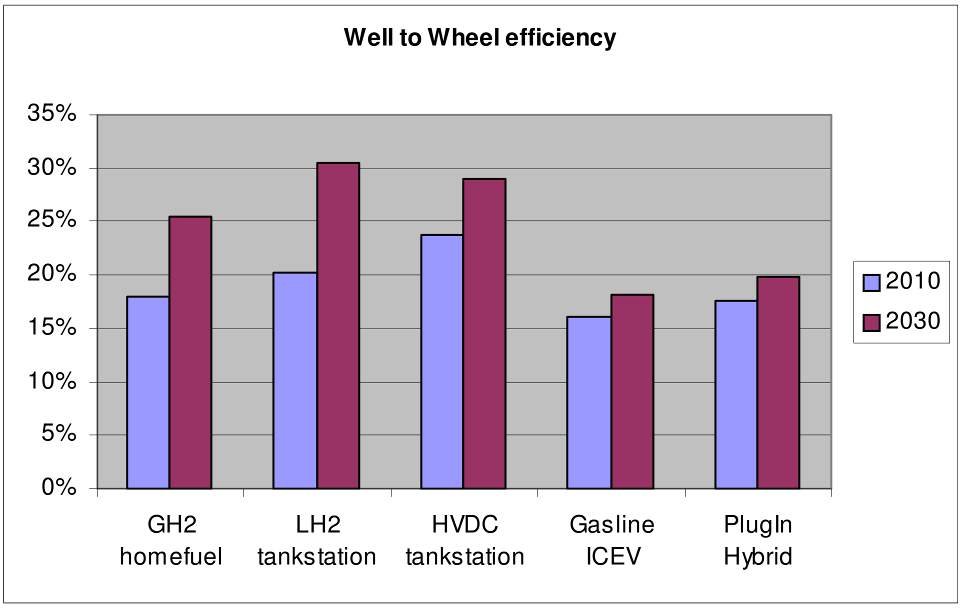


Figure 17: **Well-to-wheel** efficiencies of the three routes and 2 reference situations

From a well-to-wheel efficiency point of view all routes show improvement potential over the current gasoline fueled ICEV. Efficiencies of 26% (GH2) to 28% (HVDC) to 31% (LH2) are realistic in the time frame of 2030.

Particularly the LH2 route shows major potential due to improvements in liquefaction and electrolyser efficiencies. One of the conditions however is that the losses during LH2 shipping can be used as propulsion fuel on the ships itself[26]. The PHEV scores slightly better than the gasoline ICEV (20% versus 18%).

Energy use

Efficiency translates directly in energy required per distance traveled. Figure 18 provides an overview of the energy used by different routes expressed in MJ/100km.

- The gasoline fueled ICEV requires approximately 208MJ/100km (2030; well-to-tank); the majority of which is caloric value of the fuel used (approximately 5,0 liter gasoline), the remainder being energy required during fuel production and distribution (9%).
- The CSP scenarios require 120-150 MJ/100km (LH2, GH2 respectively) in 2030, which is 28-42% less than the ICE.
- The PHEV route requires 170MJ/100km in 2030, approximately 15% less than the ICEV.

[26] This is a realistic option; hydrogen boil-off can be controlled to the point where the hydrogen is either added to the conventional fuel, or is used to create CHP solutions on board.

It can be concluded that from a well-to-wheel perspective all CSP technologies are more favorable than the ICEV. The high efficiency of FCVs compensates for lower efficiencies of CSP from well-to-tank. In general it can be said that CSP scenarios have higher improvement potential from 2010 to 2030.

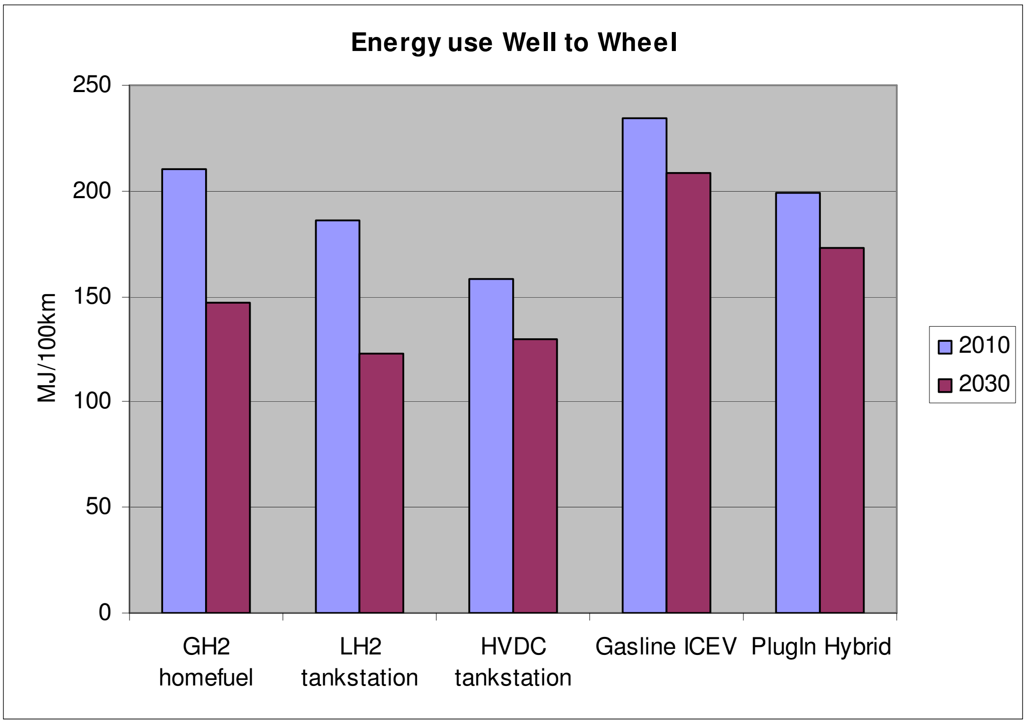


Figure 18: Energy use well-to-wheel

4.4.2 Greenhouse gas (GHG) emissions

Weinrebe et al. (1998) carried out a life cycle assessment (LCA) on two generic solar thermal power plants, an 80-MW_{el}-parabolic trough plant and a 30-MW_{el}-tower plant. The complete chain from construction, operation and dismantling was considered. The specific greenhouse potential in CO_2-equivalents for the different plant configurations range from 17 g CO_2-equ./kWh_{el} (parabolic trough plant) to 25 g CO_2-eq//kWh_{el} (tower plant) in solar mode only.

The main contribution to the GHG emissions of CSP includes the construction materials (concrete, steel, glass) and construction work itself. GHG emissions during operation in solar mode are negligible[27]. In this study an average of 25 and 17 gram CO_2/kWh is assumed for the years 2010 and 2030 respectively.

[27] Communication with DLR – May 2006. Note, in hybrid operational mode GHG emissions do occur conform to the consumption of fossil fuels. These are not taken into account in this study.

Assumptions for this study:

- GHG emissions that result from the production of (gaseous) pipelines and HVDC infrastructure are not taken into account, largely given that these factors will likely have a limited effect per unit of throughput over the lifetime of the respect-tive infrastructure.
- Electricity used for conversion steps at the CSP location (electrolysis, compression, liquefaction) is assumed to originate from the CSP location itself, thereby profiting from low GHG emissions of CSP produced electricity.
- Electricity required conversion steps at the receiving country (Western Europe) have GHG emissions based on EU-15 mix (389gr CO_2/kWh; EIA 2005).
- GHG emissions of ethanol is assumed to be 0,0082kg CO_2/MJ bio fuel (2020) (Hamelinck et al 2006).
- Data for GHG emissions resulting from shipping and trucks are derived from Ragwitz et al (2003), that studied several hydrogen pathways in detail with respect to GHG emissions.

Results GHG emissions

Figure 19 shows GHG emissions of the different routes and reference cases. In general it can be said that all CSP routes show perspectives of reducing GHG emissions significantly with a reduction potential of 70% to 95% in 2030.

- The **LH2 route** provides most GHG-reduction potential. This can partly be explained because conversion steps (electrolysis and liquefaction) are assumed to take place at the CSP location, using CSP electricity (with resulting low GHG emissions). In case liquefaction is to be carried out using conventional electricity (EU-15 mix) similar levels of the GH2 and HVDC routes would have been achieved. The majority of GHG emissions is accounted for by electricity generation by CSP; LH2 transport (shipping and tube trailer) does not add significantly to the overall GHG emissions.
- The **GH2** and **HVDC** routes have similar GHG emissions (36 and 47 gr CO_2/km in 2030 respectively). Conversion steps account for the majority of GHG emissions in both cases (GH2 homefill -73%; electrolysis filling station 80%).
- The **PHEV-reference** provides an improvement potential of 85-90% compared to the gasoline ICEV. This is mainly caused by low GHG emissions of the ethanol produced of sugarcane, combined with the low GHG emissions of CSP-generated electricity.

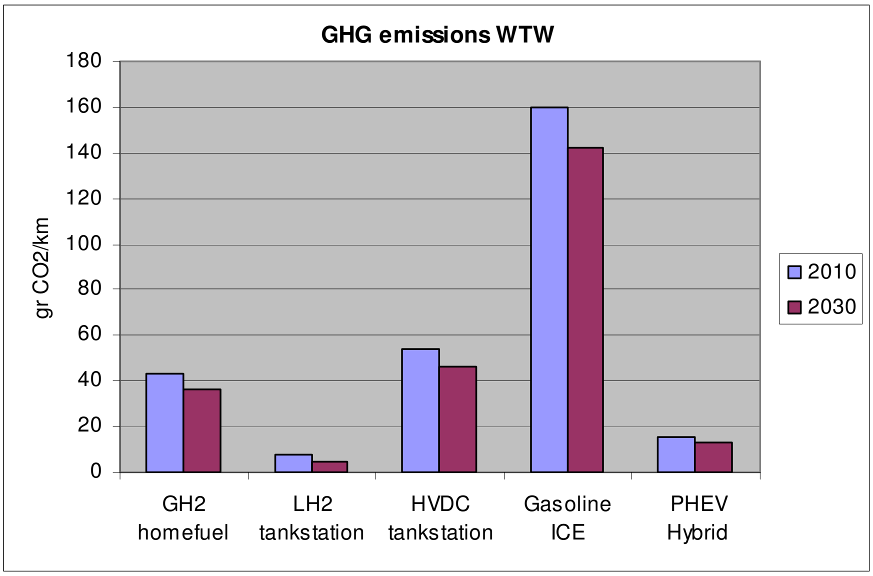


Figure 19: CO_2 emissions of different scenarios on well-to-wheel basis

4.4.3 Land use

An assessment of the required land use is made for the case in which CSP is used to provide hydrogen for FCVs in Western Europe. Particularly the comparison with bio fuels is relevant, given that bio fuel is frequently mentioned as a competing route for hydrogen as a future transport fuel.

For CSP land use is directly related to the collector or heliostat area of the solar field. Land use for CSP further depends on the latitude of the site: the closer the site to the equator, the shorter the distance between the rows of collectors or the heliostats may be.

- **CSP** Land use requirements for CSP differ for troughs (6-8 m^2/MWh/year), power towers (8-12 m^2/MWh/year) and Fresnel (4-6 m^2/MWh/year), based on available technologies (Steinhagen and Trieb 2004). It is expected that these values can be reduced with learning and scale effects. Average land use requirements for CSP of 6 m^2/MWh/year are considered in this study; this translates into 6000 GJ/ha.
- **Ethanol** Concerning land use of bio fuel production a value of 218 GJ/ha is considered, based on available data (this includes byproducts of the land used) (Hamelinck et al 2006). In the timeframe of 2030 more efficient land use can be expected; a value of 390 GJ/ha is taken into account for 2030 (Hamelinck et al 2006). Note that the (projected) land use for ethanol is approximately a factor 15 higher than CSP, indicating a relatively high land use efficiency of CSP. Given similar well-to-wheel efficiencies, this is not compensated in the rest of the chain.

- As unit of analysis the land use required to provide 20% of the Dutch vehicle market in 2030 with fuel (hydrogen or bio fuel) is chosen. This is in line with projections of penetration levels of fuel cell vehicles in this time frame (L-B Systemtechnik 2006).

It can be observed the hydrogen routes require a CSP area of 29 to 35 km^2 (2.930-3.490 hectares) to produce sufficient hydrogen to cover 20% of the Dutch car fleet. Differences lie in the well-to-tank efficiencies between the different routes: 35km^2 for GH2, 29km^2 for LH2 and 30km^2 for HVDC. The data illustrate how chain efficiencies have significant consequences for end usage (and ultimately costs).

More remarkable are the differences observed in the required land use for bio fuel production (378 km2), a factor 11-13 higher than the CSP cases. CSP thus has significant potential to reduce land requirements compared to bio fuels. Moreover, the location for CSP production is not likely to compete with alternative land use options, as is the case with bio fuels (e.g. farmland).

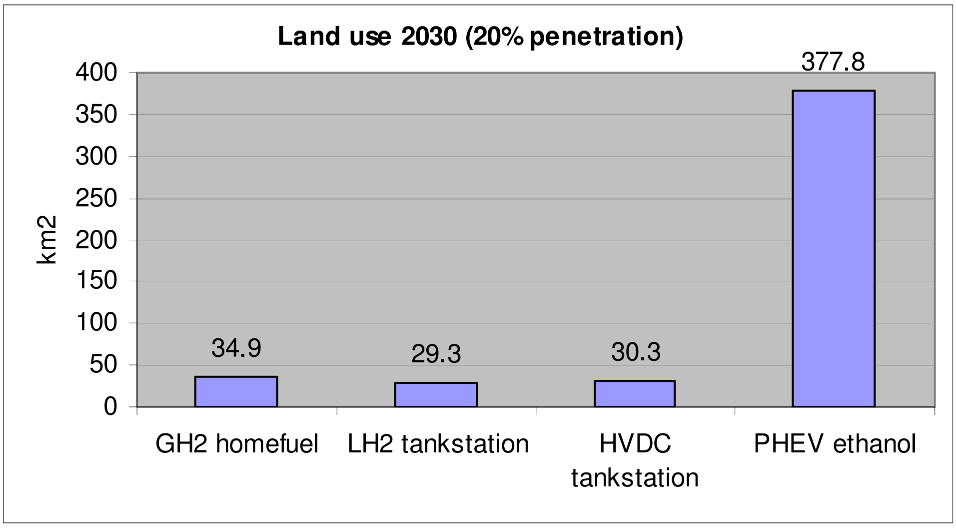


Figure 20: Land use of three CSP scenarios in case of 20% market penetration of fuel cell vehicles on the Dutch market.

The large difference between bio fuels and CSP is confirmed by other sources such as DLR (2005). Figure 21 shows minimum and maximum values for land use requirements of different renewable energy sources. As can be seen land use requirements of energy crops lie in the range of 500-1100 km2/tWh/year compared to 6-10km2/tWh/year for CSP, implying even larger differences than the mentioned factor 15.

The figure also shows how gas-oil installations on a lifecycle both have higher minimum and maximum levels compared to CSP (as found in literature by DLR 2005[28])[29]. CSP therefore does not necessarily lead to increased land use than the conventional oil and gas system.

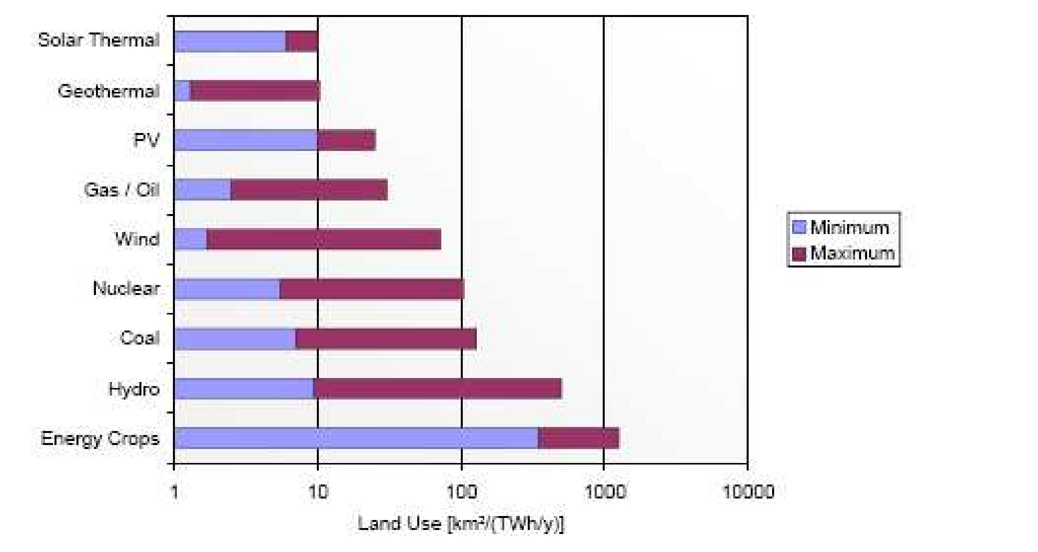


Figure 21: Maximum and minimum values for life cycle land requirements of different power technologies (DLR 2005).

4.4.4 Costs

In comparing the three CSP routes with the two reference cases in terms of costs the following assumptions have been made.

- Costs for gasoline are derived from CONCAWE (2006): €5,9/GJ. These costs are based on crude oil prices of € 25/bbl. Given high price volatility of oil prices CONCAWE includes a sensitivity analysis of oil prices of € 50/bbl (€11.9/GJ).
- Production costs for ethanol of € 6,70 /GJ (€ 0.16 /l) have been assumed; another € 1/GJ is added to cover transportation costs to Europe[30] (Hamelinck 2006). A price elasticity of 40% between oil prices and bio fuel prices has been taken into account, conform CONCAWE assumptions (€ 9,4/GJ in case of 50€/bbl).
- For CSP no price elasticity was taken into account for oil prices.
- Fuel prices include costs for production, conversion and distribution. Not considered are margins for traders and fuel taxes.
- Prices for conversion, transportation, distribution of hydrogen and CSP-based electricity have largely been derived from Ragwitz (2003).

Results: costs for hydrogen production

---

[28] This is likely related with the land use required for installations and reformation plants.
[29] The ranges in gas and oil reflect the different land use requirements of different state of technologies, from natural gas based combined cycles to more conventional cycles.
[30] Feedstock for the ethanol considered in this study is sugarcane from Brasil.

Costs for hydrogen (produced from CSP) to be delivered to the end-user range from 0,25-0,51kWh/kWh H2.

- With 0,25 kWh/kWh H2 the **LH2 route** provides the most cost-effective option for delivering hydrogen to the end-user. Cost elements include shipping costs (circa 22% of the total). The low price is largely due to limited conversion steps, leading to higher costs in alternative routes.
- The **GH2 route** suffers from high costs of the home fill installation[31]. In case GH2 would be delivered to refilling stations (rather than individual homes) costs would be slightly higher than the LH2 route.
- The **HVDC route** costs 0,28 kWh/kWh H2, largely due to high costs for decentralized electrolysis (versus centralized electrolysis).
- In general it can be said that transport costs are relatively low compared to production and conversion steps.

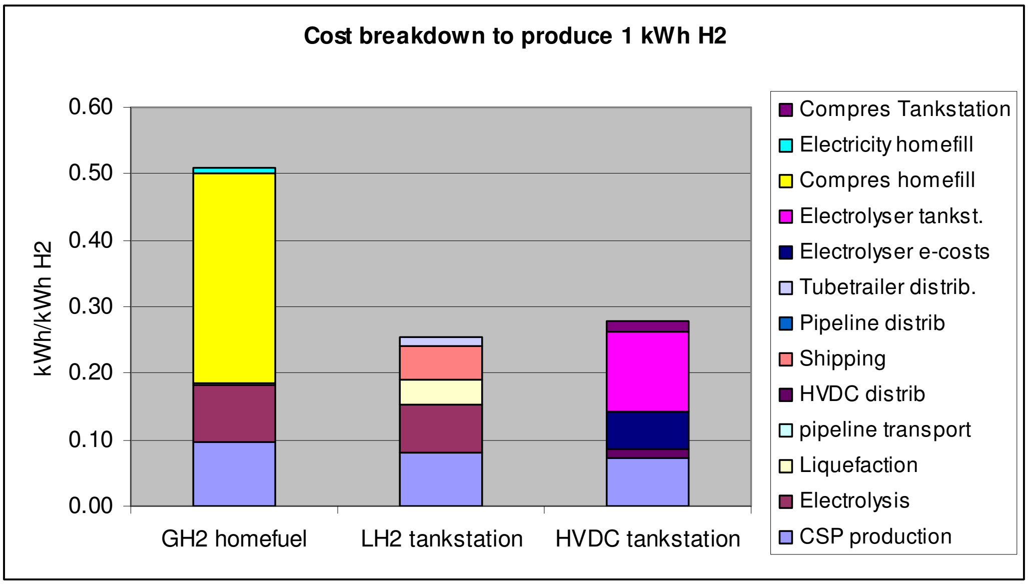


Figure 22: Cost breakdown of hydrogen produced by three CSP routes

[31] Costs of € 4.000 for a home fill station are included (conform current Natural gas homefill installations), 10 year depreciation, and average annual mileage (10.000 km/year).

Results: Comparison with reference cases

Costs for hydrogen produced from CSP leads to higher production and distribution prices for the end-user. Figure 23 shows a simplified sensitivity analysis assuming crude oil prices of € 25-50/bbl.

- In all CSP cases, hydrogen is a factor 2.5 to 5 higher than gasoline (per distance traveled). And thus, despite relative low costs of CSP electricity in 2030, the costs for hydrogen are significantly higher than gasoline.
- The **PHEV** version provides lower prices than gasoline, particularly in the case of the higher assumed oil prices. This can be explained by the relatively low ethanol prices compared to gasoline; while half of the distance is traveled on electricity generated with CSP. Due to the high efficiency of recharging and the electric motor, as well as the limited conversion steps, the electric drive is very efficient. This leads to low costs compared to the other routes.

It should be noted that CO_2-related costs have not been taken into account, which may add significantly to the current gasoline costs. Furthermore it should be considered that taxation is not included, which is an instrument available for policy makers to stimulate hydrogen application in mobility in the long term.

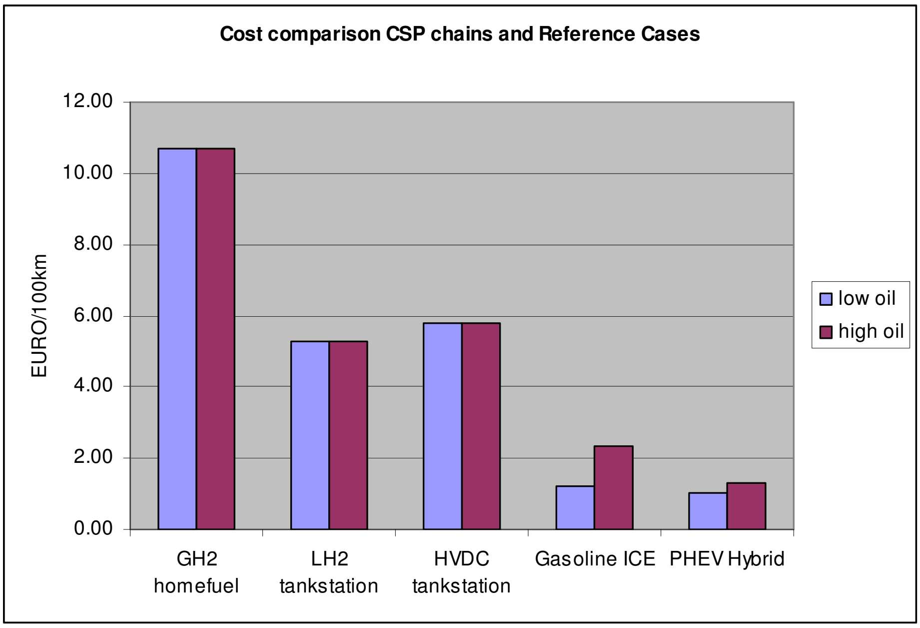


Figure 23: Cost breakdown of hydrogen produced by three CSP routes

4.4.5 Local emissions

Limited data are available for assessing the level of local emissions (NOx, SO2, CO) as a result of CSP. Most of the local emissions with CSP are produced at the production site as well as in shipping and tube trailer transport. Only levels for SO2 and NOx were found (Renewable Energy World, 2001) – table 6 provides an overview as compared to emission levels produced for PV.

Table 6: Overview local emissions solar thermal installations versus PV

	Solar PV	Solar thermal electric	Solar thermal electric	Euro IV	Euro V
	gr/kWh$_{el}$	*gr/kWh$_{el}$*	*gr/km*	*gr/km*	*gr/km*
SO_2	0.20-0.34	0.13-0.27	0.02-0.06	-	-
NO_x	0.18-0.30	0.06-0.13	0.01-0.03	0.08	0.06

The NOx levels can be compared with the EU norms set for passenger cars in Euro IV and V regulations[32] (see table 6). As can be seen, NOx emissions during CSP electricity production are significantly lower (factor 2 to 6) than the Euro V norms (to be implemented in 2008-2009). It should be noted however that NOx emissions during transport (ship and tube trailer) of hydrogen are not considered, and are likely to compensate the low emissions to some extent.
Emissions for SOx are not regulated for passenger cars – CSP levels are likely to be higher than current passenger car emissions of SOx (also given relatively high SOx levels of ship transport).

Local emission levels will not be further elaborated in this study, partly given limited data availability, but also given that CO_2 and land usage form priorities in this study. This is partly the result of significant progress achieved in internal combustion engines to reduce local emission levels, leading to a shift in policy priorities towards CO_2 and energy efficiency[33].

4.4.6 Potential effects CSP

Using a framework provided by MNP, this section shortly evaluates CSP on social, economic and environmental criteria (the latter based on the results of this study).
CSP offers significant advantages with respect to environmental performance, particularly related to lower GHG emissions as well as generating clean water (desalinated). CSP comes at the cost of increased land use for setting up CSP installations.

[32] EU directive 09/69/EC
[33] Note however that reduction of local emissions is expected to remain a policy issue given air quality problems in several European cities, as well as reduced effect of emission reduction technologies over the lifetime of the vehicle.

However, whether land use translates in significantly lower landscape quality is questionable, given that typically the non-inhabited regions are most suitable for installing CSP. This argument is less valid regarding HVDC power lines that influence landscape quality negatively.

In social terms CSP provides opportunities for both the Netherlands as well as the Mediterranean region. The large-scale supply of CSP generated electricity to the Netherlands reduces its dependence on fossil fuels, increases security of supply, while providing a more diversified portfolio of (sustainable) energy sources.

For the Mediterranean region both social as well as economic advantages can be expected. CSP provides access to energy, security of supply and independence of fossil fuels. Also it provides employment opportunities, and an opportunity to build up knowledge in a sector centered around CSP technologies. The advantages of CSP come at slightly moderately to higher electricity prices (dependent on oil prices).

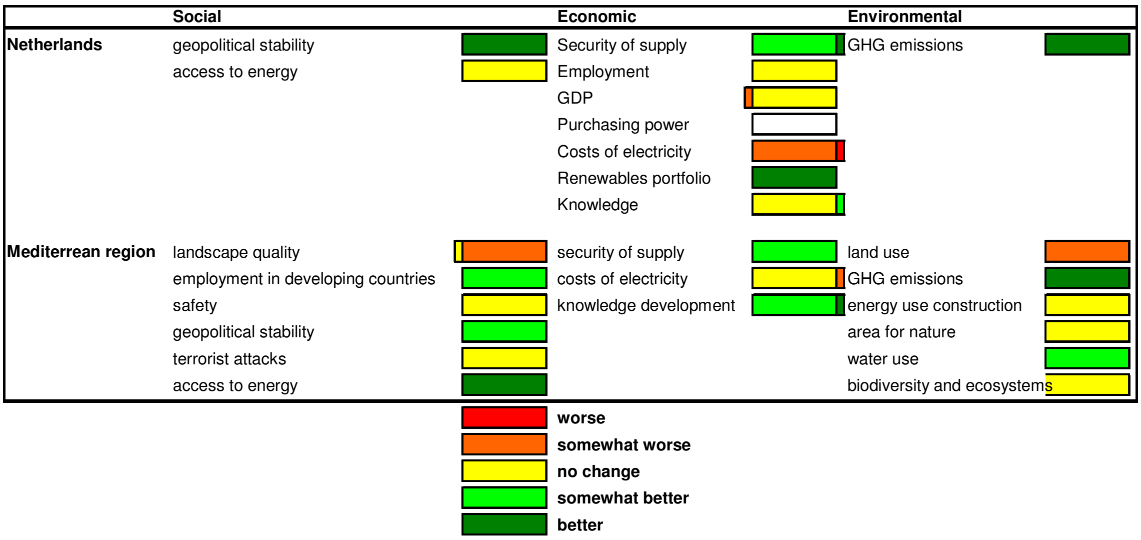


Figure 24: Qualitative assessment of social, economic and environmental aspects of CSP

4.5 Conclusions

Table 7 provides an overview of the environmental and economic comparison of the five chains analyzed. The following conclusions can be drawn.

- The CSP routes score strong on efficiency/energy use and GHG emissions compared to the gasoline ICEV reference case. Improvements of energy efficiency by a factor 1,½ -2 can be reached on a well-to-wheel basis. Particularly the LH2 and the HVDC show potential.
- In terms of GHG emission, the LH2 and PHEV case stand out. Regarding LH2 it should be noted that low GHG emissions are largely due to liquefaction at the CSP location using (low GHG) CSP electricity; in case EU mix would have been used, similar GHG levels would have been reached.
- Although limited data are available, CSP is not likely to increase land use requirements compared to the conventional gasoline route. Furthermore, the study shows that compared to bio fuel production, CSP provides major opportunities to reduce land use, while the location itself will not compete for other types of use (farmland).
- Local emissions of CSP routes are likely to be lower than the gasoline reference, although more research should be done on local emission production of CSP plants.
- The most losses of the CSP routes are made in conversion steps. For reasons of efficiency and cost reduction it can generally be concluded that conversion steps should be prevented.
- Despite relatively low costs for CSP generated electricity production and distribution costs of hydrogen will be a factor 2 to 5 higher than gasoline.

Table 7: Evaluation of CSP routes compared to two reference cases

	A ***Gasoline ICEV***	***1*** ***GH2***	***2*** ***LH2***	***3*** ***HVDC***	***B*** ***PHEV-bio***
Efficiency (WTW)	0	+	++	+/++	O/+
Energy use	0	+	++	+/++	+
GHG emissions	0	+	++	+	++
Land use	0	0/-	0/-	0/-	--
Local emissions	0	+	+	+	0
Costs	0	--	-	-	+

5 Transition evaluation

5.1 Theoretical background

For the transition evaluation of CSP and fuel cell vehicles we use a methodology developed by the Netherlands Environmental Assessment Agency (MNP). The special character of transitions and transition management asks for a different approach compared to common policy evaluations. So-called 'activity sets' that play a central role in the transition process are described: problem perception, visions, research & development, experiments and demonstration projects. National and international policies could help to shape these activities. Figure 25 below shows how these core activities will lead to the motivation or resistance to change the existing system.

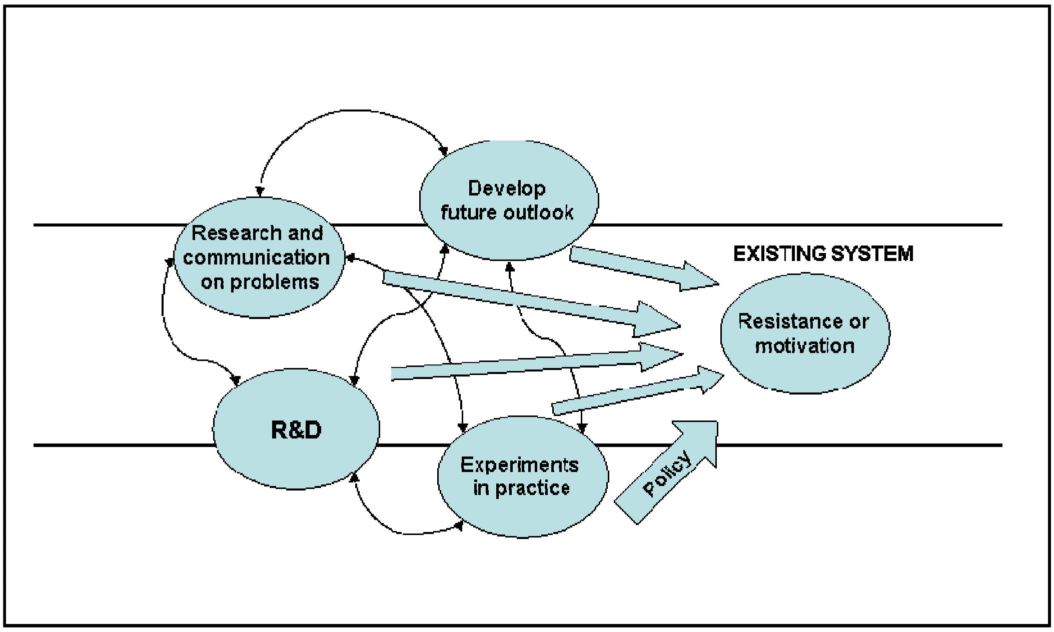


Figure 25: Evolutionary theory and considerations between system options (MNP, 2006)

The first aim of this evaluation chapter is to give an historical overview of the development of CSP plants. The analysis focuses on the period 1980 to 2005, since an important technology breakthrough came with the building of nine SEGS plants in the USA in the period 1980-1991. The second aim of this chapter is to investigate which policy influences gave direction to this technology developing process.

5.2 Evaluation of development of Concentrating Solar Power

This paragraph gives a historical overview on the development of CSP plants from its start in 1980 to now. The developing period of CSP is split up into several more or less independent and characterizing periods. This will help in describing the actors involved, research activities performed and existing policies.

5.2.1 Before 1980 –hundreds of concepts-

Oil prices in the 1970s triggered the development of renewables. Early designs of solar thermal power plants formed the basis for R&D development in the late 1970s and 1980s. Organized, large-scale development of solar collectors started this period in the United States under the Energy, Research and Development Administration (ERDA). The National Science Foundation (NSF) initiated programs directed towards the eventual commercialization of large-scale STEPS plants (Kreith and West, 1997). The basic idea seemed to be that any concept with a strong advocate deserved an opportunity to prove itself, at least through a prototype or pilot plant stage. As a result there were literally hundreds of concepts in different stages of development (Kreith and West, 1997). There was no definitive system to eliminate others from further development.

5.2.2 1980-1990 –First commercial plants built-

In the period 1980 to 1990 solar thermal projects were undertaken in a number of countries: United States, Russia, Japan, Spain and Italy. Initial feasibility studies identified three alternative systems: parabolic through, central tower and dish systems. Many of the pilot plants undertaken by these countries failed to reach the minimum performance levels. Further research and development was needed.
The world’s largest Solar Energy Generating System (SEGS) was built in the Mojave Desert in California, USA. Nine solar thermal power plants were built in the period 1984-1991 with a total capacity of 354 MW_e.

Visions

The main reason that solar thermal power gained attention in countries like the United States, Russia, Japan, Spain and Italy was because of increasing oil prices. These high oil prices made CSP more competitive to conventional energy technology. These days CSP was not widely recognized as a suitable option to supply electricity in other countries.

Stakeholders/actors

All projects are undertaken in countries that have national governments supporting the solar thermal power technology. This time the network around the CSP technology was not so large. Only a few technology suppliers and project developers around the world were actively involved in the projects established. No strong network of stakeholders was in place to bring the CSP technology to the market.

R&D (industry and government)

Of the hundreds of concepts that marked the beginning of the development of CSP only a few survived. These systems were selected because they showed high potential to become commercially viable. Research programs and evaluations were carried out to overcome the most important barriers to commercialization. Many of the pilot plants established in the 1970s failed to reach the expected performance. Most of them were funded by national governments (Greenpeace, 2005).

In Europe some other important impulse to research on CSP was given. In 1981 the Plataforma Solar de Almeria (PSA), Spain's R&D platform for CSP technology, came into being. Nine countries promote the 'Small Solar Power Systems' project, under the umbrella of the International Energy Agency. In 1987 the 'German-Spanish Agreement' begun to collaborate at the PSA. By the end of 1998 the German government decided to terminate the 50-50 cost sharing agreement with Spain at the PSA. CIEMAT took over the full burden of PSA financing activities. By the year 1990, the PSA is classed by the European Commission for the first time as a 'Large-Scale European Research Facility'. The PSA would build up a long tradition as a venue for international cooperative projects. All various solar thermal technologies could be tested and solar thermal experts from all over the world came together at the PSA.

Demonstration projects

A major technology breakthrough was achieved when the American/Israeli company Luz International started to build parabolic through power stations in series (Greenpeace International, 2005). Between 1984 and 1991 nine SEGS were build in the Mojave Desert (USA). All plants use trough technology and each plant was by far larger than any of the research pilot plants. The electricity generated was dispatched to the Southern Californian Grid. It were the first solar power plants developed, financed, built and still operated on a purely private basis (European Commission, 2004).

The plants could be established because Luz International could sign attractive long term power purchase contracts and could apply for Federal and State tax incentives (GreenPeace, 2005).

Also a number of solar towers have been built during the 1980s as research and demonstration projects. However, none of them are still in operation, because required performance levels were not met. The Solar One, built in 1982, produced over 38 GWh before it was discontinued in 1998. Solar Two was an upgrade of Solar One, built in California in 1996. This 10 MW_e solar tower that operated from 1997 to 1999.

Policy

High energy prices primarily led to the attention for alternative ways of providing energy. But high energy prices alone seemed insufficient to make investments in CSP attractive. In the United States other circumstances favored the construction of the nine SEGS plants in the Mojave Desert: Federal and State tax credits, and attractive power purchase contracts. When high fossil fuel prices coincided with the withdrawal of tax credits and a change in the mandatory purchase contracts, Luz International became bankrupt in 1991 (Greenpeace, 2005). It seems that national policies supporting CSP are of great importance for the successfulness of the projects.

5.2.3 Period 1990–2000 - No commercial projects-

Visions

During the early 1990s we see a move away from CSP technology. The construction of solar power plants stopped because of several reasons like low oil prices and liberalization of electricity markets. Another reason was that electricity from CSP technologies proved to be still higher generating costs compared to fossil-fueled plants. The favorable framework conditions in California (USA), which enhanced the construction of the nine SEGS plants, deteriorated in the early nineties. This changed the market environment.

In this period we also see that developments were going on, not physically by the construction of new plants, but on a governmental level where long term policies were formulated. During this period the European Union started its policies concerning renewable energy, implicitly holding targets for solar thermal power.

Stakeholders/actors

The market environment for CSP industry and developers changed when a different situation was faced. The CSP players that left after the demise of Luz were pure component manufacturers. They had no experience with project development and had to adapt to this new situation where no attractive regulation was in place (Aringhoff, 2002).

Activities within the CSP technology field mainly took place on a governmental level. No commercial activities were undertaken during this period, there was no market for CSP and commercial interests were very low.

R&D

The rising environmental concern drove research and development activities. While this fundamental research continued, the knowledge was not used in any commercial projects. No experience could be gained with the CSP technology in real, but several research groups worked on improving the technology.

Policy

In 1997, the European Union set targets for concentrating solar thermal in its "White Paper for a Community Strategy and Action Plan: Energy for the Future: Renewable Sources of Energy"(European Commission, 1997). One of the objectives that implicitly holds targets for solar thermal power was to increase the share of renewable energy sources in the gross energy consumption to 12% and in electricity generation to 22.1% by 2010. A target of 1 GW_e for 2010 is set for all renewable energy sources together that did not yet achieve significant market penetration: concentrating solar thermal technologies, ocean energy systems and enhanced geothermal systems (European Commission 2004). This target is only marginal when compared to the targets for biomass (90 Mtoe)[34], wind (40 GW_e) and hydro (13 GW_e).

In 1996, the World Bank established a financing program, through the Global Environment Facility (GEF), to fund up to US $50 million of the incremental cost of a concentrating solar thermal installation within a conventional power plant in developing countries (Greenpeace, 2005).

5.2.4 Period 2000–2006 - Renewed interest -

Visions

This period is characterized by a renewed interest in solar thermal power as a large scale option to produce zero-emission electricity. Together with the speed up of the implementation of wind energy potential in industrialized countries like Germany, Spain and the USA, the need for reliable, renewable and dispatchable peaking power coverage becomes more visible (Greenpeace, 2005). The variable nature of wind power supply and the varying loads ask for additional provisions to secure the energy supply. The possibility to store thermal energy from CSP technologies is seen as part of the solution for a secure energy supply. It is relatively easy to store the energy in water tanks and deliver it at the times it is needed. This convinced governments in Spain and the USA to launch incentive programs to attract private investment in solar thermal independent power projects (Greenpeace, 2005). Also the availability to dispatch power during peak demand has motivated national governments to revive the support for CSP.

Stakeholders/actors

Before 2004 there has been no market perspective for CSP plants in developed countries. This changed when initiatives to join forces started and when some countries made a clear commitment to CSP technology. Nowadays, a number of influential groups exists that promote the development and commercialization of CSP technology. In the European Union three countries are committed to CSP: Germany, Spain and to a lesser extent Italy.

[34] Of which 20 Mtoe electricity (230 TWh) and 70 Mtoe heat.

A clear overview is given by Wenzlawski (2003). In that study four different types of actors are distinguished that advocate CSP: Development Finance Institutes (DFI), Government Ministries, Public Research Institutions and advocacy groups. These are listed in Table 8.

Table 8: Overview of actors involved in stimulating the development and commercialization of CSP (Wenzlawski, 2003)

Organization/Institution	Objective	Country
EIB (European Investment Bank)	DFI (Development Finance Institution)	Europe
EU - Commission	DFI (Development Finance Institution)	Europe
GEF	DFI (Development Finance Institution)	International
KfW (Kreditanstalt für Wiederaufbau)	DFI (Development Finance Institution)	Germany
World Bank	DFI (Development Finance Institution)	International
BMU (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety)	Gov. Ministry	Germany
DOE (Department of Energy)	Gov. Ministry	USA
Ministry of Economy	Gov. Ministry	Spain
Ministry of National Infrastructures	Gov. Ministry	Israel
CIEMAT (Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas)	Research Organization	Spain
DLR (Deutsches Zentrum für Luft- und Raumfahrt)	Research Organization	Germany
Fraunhofer Institute for Solar Energy Systems	Research Organization	Germany
NREL (National Renewable Energy Laboratory) [Sunlab]	Research Organization	USA
Sandia National Laboratories [Sunlab]	Research Organization	USA
Weizmann Institute of Science	Research Organization	Israel
ESTIA (European Solar Thermal Power Generation Industry Association)	Advocacy Group	Europe
IEA/SolarPACES	Advocacy Group	International
SEIA (Solar Energy Industries Association)	Advocacy Group	USA

On European level both political and financial support is given to CSP. This support is necessary because without it solar thermal power will remain at a competitive disadvantage. The European Union has set an ambitious target of 22% of Europe's total electricity consumption to be from renewable sources. Within this framework, CSP could be developed.

Next to the European Commission other national and international development and finance institutions are financially supporting CSP: European Investment Bank, Global Environment Facility (GEF), Kreditanstalt für Wiederaufbau (KfW) and the World Bank (Wenzlawski, 2003).

In 2004, the CSP project GEF portfolio comprises four projects, India, Egypt, Morocco and Mexico (Philibert, 2004). The GEF has been unsuccessful in its starting years because of country and technology risks, and a weak industry. None of these GEF supported projects have been brought to construction thus far. Also the fact that developed countries had no market perspectives for CSP before 2004 hampered the implementation of the GEF projects. There were too little incentives for power plant bidders (Philibert, 2004).

Governmental ministries in Germany, Spain, USA and Israel are evident on a national level. In Europe, CSP is most promoted in these countries. Their aim is to shape conditions for the CSP market implementation.
Research institutes have been key players from the start of CSP development. At the moment the industry gets more and more involved in the development and commercialization of CSP technology. Research projects are not only carried out by research institutes, but industry also takes parts and coordinates some projects (see Table 9). Advocacy groups then are operating both on national and international scale to influence political decisions and bring the view of its members. The major groups are ESTIA and the American SEIA (Wenzlawski, 2003).

The fact that no plants have been built after the nine SEGS plants in 1992 and that the industrial teams of that time disappeared, made bidders hesitant to take the high risks related to these projects. After the introduction of the feed-in law for CSP electricity in Spain (2002 and 2004), this changed and more companies are expressing their interest in CSP plants. While before small technology supply companies with little financial background guaranteed the risks, now larger companies are willing to takeover the wrap around guarantees for the entire solar plant (Philibert, 2004).

R&D (industry and government)
The Fourth and Fifth Framework of the European Union contributed with 22 €M to the development of CSP technology. Trough technology receives about 40% of total support. Research focuses mainly on cost reduction and developing the receiver technology (Greenpeace, 2005). An additional 15 €M has been used for demonstration projects under FP5.

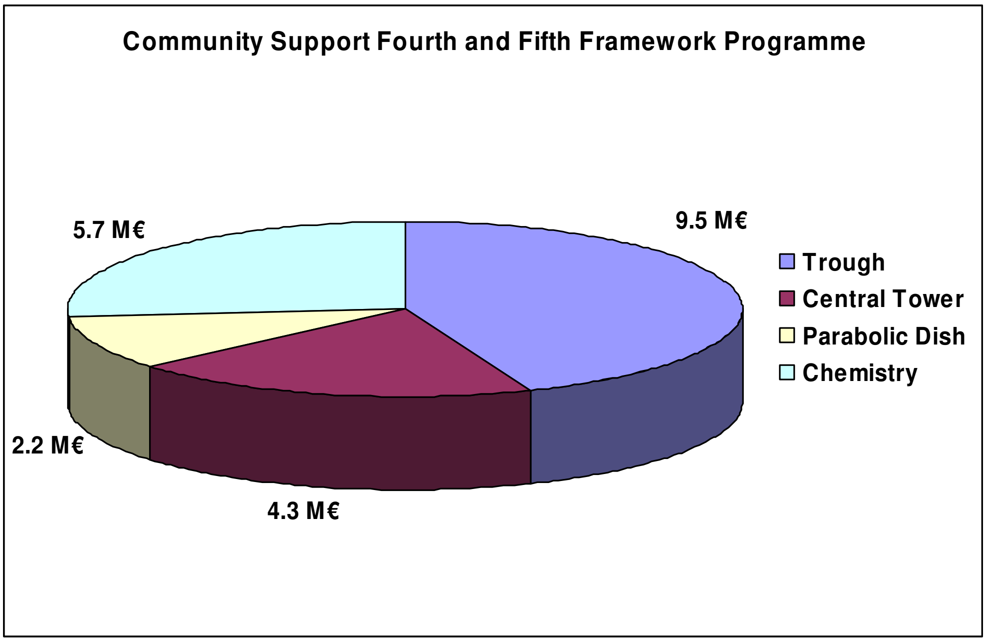


Figure 26:Framework Program Support for CSP projects in M€ (source: (European Commission, 2004)

In table 9 an overview is given of all European research projects in the field of solar thermal power. Careful analysis shows some interesting features of the type of projects performed. Most of the projects focus on cost reductions of the different CSP technologies. We see a shift from projects led by research institutes (like CIEMAT) towards industry led projects. This indicates that projects come out of their research phase and that the focus is on application of the technology to a real situation and demonstration at a larger scale (European Commission, 2004). The Eurotrough I and II projects were performed to rethink the parabolic trough collector design originating from the 1980s and to build cheaper and more efficient versions. The industrial partners of these projects are now EU leaders in low-cost parabolic trough technology and are beginning to tender for projects using the Eurotrough design.

The Hydrosol project is important for the system option analyzed in this study: the transition towards fuel cell vehicles using solar thermal energy. At the start of this project the production of hydrogen using CSP was more a theoretical investigation. A few very small scale reactor testing was involved. The industrial partners involved (HelioTech Aps, Johnson Matthey Fuel Cells) are of great importance to ensure fast commercialization of the project results and their integration with hydrogen technologies.

Table 9: Research areas 1994-2004 (European Commission, 2004)

European research projects	Research topic	Start of project & Status	Project leader	Total cost (€)	EC funding (€)
DIrect Solar Steam (DISS)	Solar Through: Direct Steam Generation	1996-1998 Completed	Ciemat (research)	4.280.996	2.000.000
DIrect Solar Steam – Phase 2 (DISS-2)	Solar Through: Direct Steam Generation	1998-2001 Completed	Ciemat (research)	5.592.620	2.500.000
Integration of Direct solar steam technology for electricity production (INDITEP)	Solar Through: Direct Steam Generation	2002-2005 Completed	Iberinco (utility)	5.592.620	2.698.785
EUROTROUGH I	Solar Through: Collector Development	1998-2001 Completed	Instalaciones Inabensa, S.A.	2.402.514	1.199.899
EUROTROUGH II	Solar Through: Collector Development	2000-2002 Completed	Instalaciones Inabensa, S.A.	1.993.707	996.851
SOLAIR	Central Tower: Volumetric Air Receiver	2000-2004 Completed	Instalaciones Abengoa	3.312.110	1.497.092
SOLGATE	Central Tower: Pressurized Air Receiver	2000-2003 Completed	Ormat Industry Ltd	3.156.120	1.498.772
EURODISH	Dish/Stirling: System Development	1998-2001 Completed	Schlaich Bergermann und Partner	1.665.531	750.000
HYPHIRE	Dish/Stirling: Hybrid System	1996-… Completed	Deutsches Zentrum fur Luft- und Raumfahrt	1.775.003	971.894
SOLASYS	High Temperature Solar Thermo chemical Gas Reforming	1998-2001 Completed	Deutsches Zentrum fur Luft- und Raumfahrt	2.536.077	1.568.320

European research projects	Research topic	Start of project & Status	Project leader	Total cost (€)	EC funding (€)
SOLZINC	High Temperature Solar Thermochemical system: Metal Production	2001-2005 Completed	CNRS-IMP	3.018.632	1.284.282
HYDROSOL Two industrial R&D partners and three research partners	High Temperature Solar Thermochemical System: Hydrogen Production	In Progress	Center for Research and Technology-Hellas/Chemical Process Engineering Research Institute	2.634.300	1.317.149
			Total	**37.960.230**	**18.283.044**

From Table 9 it turns out that Spanish and German parties take the lead in these European projects. Several other countries also have own research teams, located in Belgium, France, Italy and Switzerland (IEA, SolarPACES Annual Reports).

Demonstration projects

There is a need for technology deployment to reach cost goals. R&D in itself does not introduce the technology on the market. Deployment contributes to cost reduction in two ways: industry can take advantage of mass production and benefits from scale-up of the technology can be achieved.

In 2003, demonstration projects with a total capacity of 2.7 GW_e in the pipeline are planned worldwide. Most of them should start commercial operation before 2010. This total planned investment represents € 4.5 billion, including € 200 million of GEF grants and € 15 million of grants for demonstration projects from the EU FP5 (European Commission, 2004).

In Europe most initiatives for solar power projects are undertaken in Spain as a direct consequence of the Royal Decree 436 of March 2004. All projects under development in Spain use either central tower or parabolic trough technology. Of the 200 MW currently building or lined up with permits, about 70 MW will use central tower technology. Another 800 MW is planned to use trough technology (Stirzaker, 2006). The first commercial projects, PS10 and Andasol I and II, are being developed in Spain. They are seen as results of R&D activities under the FP5 program. The first plant 'PS10' is a 11 MW_e central tower system producing electricity to the grid.

The second project consists of two units of 50 MW_e each, using parabolic trough collectors with storage capacity. Each project is supported by the FP5 with € 5 M. These projects might strengthen the European CSP industry in the worldwide electricity generation market and encourage the construction of new installations.

A consortium of Spanish, French, Czech and US companies, called Solar Tres, recently received € 5 million from the EU to help promote a new 15 MW power tower plant utilizing the technology currently in use in Barstow, but which would be approximately three times the size. So far, however, the group has been unable to attract US government funding due to a lack of interest in the technology. Despite this, they are still hoping to have the project completed in the coming years.

Policy

Some member countries of the European Union launched initiatives to support the CSP technology: Spain, Italy and Germany. In March 2004, the Spanish government introduced the first feed-in tariff for concentrating solar power[35]. The 2004 law establishes two alternative payment schemes, both guaranteed over the 25 year life-cycle of CSP plants, and diminishing thereafter. The first is a fixed, guaranteed payment of 300% of the Average Reference Tariff (ART) for electricity. The second induces operators to compete on the national wholesale electricity market. Here, CSP generation receives 250% of the Average Reference Tariff plus a 10% additional incentive. Furthermore, for the first time, the RD 436 allows all renewable thermal installations to use fossil fuel backup. In case of CSP this can be as much as 15% of overall capacity. So far, all Spanish CSP projects have opted for natural gas as backup (Stirzaker, 2006).

New life has been put into projects that have been at stake but never realized since the 1990s (about 200 MW). Applications for about 800 MW of new projects have been received since this new regulation is in place (Stirzaker, 2006). In 2005, the Spanish utility Iberdrola announced a pipeline of ten parabolic through projects totaling 500 MW across six regions. Other through projects are undertaken by Solucar that has a parabolic through portfolio of 300 MW. Although no explicit choice for the type of CSP technology has been made until now, short term development of solar thermal power mainly focuses on the parabolic through technology. Of the 200 MW currently building or lined up with permits, 50 MW will use central tower technology, all developed by Solucar. An additional 17 MW tower project, Solar Tres, built by aerospace and engineering firm Sener, has matured since 2000 and the developer hopes construction to start in 2007. But that is where existing central tower developments end. The remaining CSP projects under development, nearly 800 MW in all, plan to use trough technology.

[35] Royal Decree 436/2004

In 2001, the Italian Parliament provided capital grants of € 100 million to the National Agency for New Technology, Energy and the Environment (ENEA) for the development of solar thermal-electric generation. In the period 2001-2003 funds were assigned to ENEA to set up research and development activities in the field of solar thermal and fuel cells (Financial Law 388 of 23 December 2000). Two decrees in 2001 defined quantitative targets, functioning and implementation of programs related to energy conservation and efficiency as they relate to the opening of the electricity and gas markets. Solar thermal, photovoltaics and biomass are eligible for support. The targets are gradual and progressive from 2002-2006 (http://www.iea.org/textbase/nppdf/free/2004/renewable2.pdf).

In 2001, Germany launched a R&D program on high-temperature solar thermal power generation technologies with a budget of € 10.5 M (European Commission, 2004). For the period 2001-2004, the research on high temperature solar thermal received 4.5% of the energy research funding. The Federal Ministry of Economics and Labor funds both basic research and application-oriented research including the demonstration of innovative technologies (Federal Ministry of Economics and Labour, 2005). Germany has a great interest in solar thermal power both from the aspect of climate policy and for industrial policy (Federal Ministry of Economics and Labour, 2005).

Other activities

In the past ten years, international technology collaboration in the field of CSP took a jump. Today, three initiatives are most important in terms of bundling efforts around concentrating solar power, namely the IEA technology implementing agreement SolarPACES, Global Environment Facility (GEF) and the Global Market Initiative (GMI) of July 2004. The IEA SolarPACES Implementing Agreement was initiated in 1977 as a cost-shared collaboration under the former name Small Solar Power Systems. As of 1997 the goal of the agreement changed from focusing on technology development to one addressing all activities needed to overcome barriers to large-scale adoption and implementation of CSP technology. The Plataforma Solar de Almeria was initiated as an IEA project under the SolarPACES agreement. Originally it was financed by Europe and the US. Since 1988 financial support was taken over by Germany and Spain. Over 25 years, SolarPACES has established a strong and efficient network with CSP experts from research, industry and utilities. There is no other academic network in the field of solar concentrating technology (OECD/IEA, 2004).

In July 2004, the Concentrating Solar Power Global Market Initiative (GMI) was launched. The goal of this international public-private partnership was to facilitate the realization of 5,000 MW_e of new CSP plants by 2015. Participation is open to governments that have the resources for CSP technology or can deliver industrial capability. The GMI recognized that one needs to share experiences and learn from each other when it comes to the commercialization of a new technology.

5.2.5 CSP in The Netherlands

Although the Netherlands have not left its mark on the CSP development, the attitude towards CSP is currently changing. There has been very little commitment to this technology until last years. One of the most active Dutch stakeholders is the organization GEZEN, founded in 2004 that started its promoting activities in the field of concentrating solar power. The aim of this organization is to make the advantages of CSP more widely known as a solution to the global energy scarcity, drinking water problems and climate change (Website GEZEN, 2006).

In 2006, CSP is seriously discussed in the Dutch government. Whereas the Netherlands before thought that they should not be involved in CSP, now the opportunities are explored to take an active role. Although it is not possible to build CSP installations in the Netherlands, there are other ways to be involved in this technology. The future perspectives in terms of costs and performance of this technology are bright and therefore for a country like the Netherlands, it is wise to get acquainted with this technology.
The Energy Advisory Council asked the Dutch government to pay attention to CSP and discuss the possibilities to start up activities in this field. The Netherlands are exploring different options at the moment how to take up CSP in the activities in the field of sustainable energy and developing cooperation. Also the role that CSP could play in interconnecting the Mediterranean region with Western Europe within the context of a future secure energy supply is discussed. Today, several organizations (among which GEZEN) argue that a new transition path 'solar energy from southern EU member states' must be established. The current situation prohibits that solar energy projects outside the Netherlands apply for subsidy. Another issue is how the Netherlands can promote the CSP potential in EU context (Energy Advisory Council, 2006).

At the moment, few Dutch companies are active in the CSP field and no research and development activities are exploited. The following Dutch companies have plans to carry out CSP or CSP related activities (Du Marchie van Voorthuysen, 2006):

- SOLAQ was recently established to explore the possibilities for the construction of solar thermal plants on specific niche markets.
- Zonneboer Solar Solutions develops small-scale CSP projects with emphasis on water desalination.
- Plantium Consulting and Construction is going to develop CSP projects.
- Tri-O-Gen BV is a technology supplier of ORC turbine-generators for units of 175 kW.
- Water Technology Holland owns the commercial realization of the MEMSTILL desalination technology, developed in the Netherlands.

The projects are in the planning phase at the moment and none of them is actually in the take-off phase. These companies currently focus on niche markets to bring CSP technology to work. CSP in combination with sea water desalination is a concept developed by SOLAQ, Zonneboer Solar Solutions, and Plantium Consulting and Construction. SOLAQ specifically aims to develop CSP projects combined with desalination of sea water on island economies. CSP technology can be competitive with alternative energy supply options when energy prices are high. SOLAQ for example investigates whether CSP can be implemented in less competitive markets and difficult accessible areas, such as islands (Solleveld, 2006).

The reason that Dutch projects have not yet started is that technology costs are too high at the moment and small scale projects are not commercially viable. The Dutch company Plantium for example experienced difficulties to attract investors for their projects (Lubbers, 2006). The lack of support in the Netherlands is also not a favorable condition for CSP plants to be built. It is important that CSP gets governmental support in the nearby future to catch up with international developments and build up knowledge on the CSP technology. In the first place, financial support is necessary, but also the commitment of Dutch universities to set up research activities in the field of CSP is required (Solleveld, 2006).

The Netherlands versus Germany

Although things are moving in the Netherlands at the moment there is a large difference with the German attitude towards CSP. Germany has been supporting CSP technology for more than 20 years now. Germany has more or less the same resources compared to the Netherlands and will therefore most probably not exploit solar thermal plants in Germany. There are other reasons that Germany is so actively supporting CSP. First, German industries have been involved in component manufacturing for CSP plants for a long time. They have built up experience with the technology and now are among the most important technology suppliers in the world. Also several project developers (turnkey suppliers) and consulting firms are based in Germany.

Secondly, Germany sees the advantage of a Euro-Mediterranean network that distributes solar generated electricity to Western Europe. Germany has been doing extensive research on interconnecting the electricity grids of Europe, North Africa and the Middle East (DLR, 2006). It is unclear how the Netherlands is less sensitive to these prospects. It is likely that CSP has been higher on the agenda for a longer period of time, and has gained more know-how through extensive research projects.

5.2.6 Conclusions transition evaluation CSP

The historic evaluation of solar thermal power shows that development of this specific technology has undergone major changes over the years. In Table 10 the CSP development is shown per period. Still, none of the technologies developed reached its market breakthrough and no explicit choices have been made for one of them. CSP installations are more in the demonstration phase than in the commercial employment phase. The US CSP plants can largely be explained by high oil prices and local supporting mechanisms.

Where production plants were built between 1980 to 1990, the 1990s are more characterized as R&D rather than demonstration of CSP (in Europe mainly in Spain and Germany). Renewed interest is observed in the late 1990s (White Paper in 1997) given the perspectives of CSP to contribute to GHG reduction and the shift towards a sustainable energy supply. Moreover the flexibility of CSP to switch to fossil fuels is a major advantage, while Germany sees opportunities in importing CSP generated electricity.

Over the years we see that the commitment of national governments to CSP has been of considerable importance. European countries like Spain, Germany and Italy established R&D programs, which however not resulted in the development of commercial plant projects. The introduction of the feed-in tariff in Spain led to the first commercial plant in Europe to be developed: PS10, a central tower installation. This market creation policy measure supplies compensations for CSP electricity.
The 4th and 5th European Framework Programs have supported a significant number of European projects on solar thermal power technology. R&D support can be seen as an important condition for continued improvements and technological knowledge development to get CSP closer to commercialization.

Apart from support programs initiatives on technology collaboration in the field of CSP came up or intensified: the Global Market Initiative (GMI), IEA SolarPaces, Global Environment Facility (GEF). These initiatives address the need for sharing information between experts on an international level.

Table 10: Summarizing table on events in development of CSP technology

Period	**Stakeholders**	**Technology**	**R&D**	**Demonstration projects**	**Policy**
Before 1980 Search for viable technology hundreds of concepts	National government (USA)	Three alternative systems: trough, dish, central receiver	National research teams Extensive research on most promising concepts	Series of modular trough technology	USA: National Science Program Federal support in France, Germany, Spain, Japan
1980-1990 First commercial CSP plants built	National governments (USA)	Trough		Nine SEGS plants in USA, 354 MW_e central receiver pilots decommissioned	
1990-2000 Unfavorable circumstances for CSP: high energy prices, electricity market liberalization	European Commission National governments (Germany)		Large scale European research facility: PSA, Spain Collaboration Germany and Spain	No new plants constructed	1997: EC, White Paper - > 1GW_e for CSP, ocean, geothermal by 2010
2000-2006 Renewed interest in CSP	National governments (Germany, Spain, USA, Italy) Utilities Industry	Trough Parabolic Dish (niche market) Central Tower	FP5 and FP6: € 22M, € 15M for demonstration projects Hydrosol project Italy: four year development program (100 million Euro) Germany: R&D program of € 10.5 M	2003: 2.7 GW_e projects in the pipeline, operating before 2010 (grants from EC and GEF) Of which in Spain: 1000 MW_e, over 800 MW_e uses trough technology	Implementing Agreement SolarPaces Global Market Initiative Policy instruments: Feed-inn tariff Spain

Evaluation of development fuel cell vehicles

The historical development of fuel cell vehicles as an alternative to vehicles with traditional internal combustion engines (ICE) is described in three distinct periods: 1990-1995, 1996-2000 and 2001-2006. The year 1990 is chosen as the starting point as there were no significant activities prior to this year. Given the international arena of the automotive industry, the transition evaluation takes on an international perspective, including both descriptions of activities in Europe as well as in the United States and Japan. Lastly, the stakeholder analysis concentrates on the automotive industry given its prominent role in the development of fuel cell vehicles, but also considers activities of governments, oil industry and supplying industry of fuel cell technologies to sketch the development of fuel cell vehicles over the last decade.

Before 1990 - Alternative fuel cell applications -

Research and development in fuel cell technology goes back to the 1960s. Schaeffer (1998) shows how from 1960 to 1990 a shift occurs in research focus from alkaline and phosphor acid fuel cells towards molten carbonate, solid oxide and polymer electrolyte membrane fuel cell types. Mostly these fuel cell types were targeted for stationary applications (combined heat and power), or for niche markets in the space industry (e.g. NASA), largely due to weight and volume characteristics of fuel cell systems.

Only in the late 1980s significant progress is made on the so-called polymer electrolyte membrane (PEM) fuel cell technology, particularly related to energy density which had formed a formidable barrier for this technology in the past. Its low operating temperature and its progress on current density and power density provides perspectives for low weight and volume fuel cell systems for automotive applications with zero emissions. At this time no structural funds are available for fuel cell technology with automotive applications. In this period limited funding programs were available for fuel cell developers, the most prominent one being Ballard, Canada. By its experiments with different membrane technologies, Ballard is first to achieve major improvements in the energy density of the PEM fuel cell and, in the years to come, becomes one of the market leaders in this technology.

Period 1990–1996 - Exploring perspectives for fuel cell vehicles -

The first carmaker to get involved in fuel cell vehicles was Daimler-Benz in 1991/1992. Through its space program they had already gained experience with progress in fuel cell technology and this knowledge led to the development of several prototypes in the early 1990s. Several of the largest carmakers worldwide followed. Most of the fuel cell related activities resided in research departments rather than in development departments. Most prototypes demonstrated in this period are fueled by hydrogen (gaseous or liquefied).

Increasingly stringent emission regulation formed an important driver in the development of fuel cell vehicles. Particularly, the zero emission regulation in California, setting a quota that 10% of sold cars by selected carmakers should be zero emission cars, required carmakers to look for alternatives to conventional ICE powered vehicles (CARB 1990).

Visions

Fuel cells provided the opportunity to achieve vehicles with zero emissions, fuel cell vehicles would therefore be an alternative for battery electric vehicles for achieving the ZEV requirements posed in California[36]. Furthermore, fuel cell vehicles have relatively high efficiency on a well-to-wheel basis and have the potential to become independent of fossil fuels[37]. From a technical point of view fuel cell vehicles provided a good solution for major environmental hurdles.

Nevertheless, until 1996 the majority of efforts of carmakers were focused on electric vehicles. The general consensus in industry was that fuel cell vehicles would not be able to become commercially viable in 10 to 20 years. Rather, fuel cell technology was perceived as the successor of battery electric vehicles, developed by most carmakers in this period. Fuel cell technology was believed to provide range, power and fast refueling, which are the major hurdles associated with batteries (Van den Hoed 2004).

Stakeholders/actors

At this stage the most important stakeholders in the development of fuel cell vehicles are fuel cell manufacturers and carmakers. Fuel cell manufactures were concentrating in Canada, Germany and the US. Most large carmakers in Japan (Toyota, Honda, Nissan), US (e.g. General Motors, Ford, Chrysler) and Germany (Daimler-Benz, BMW) developed their own fuel cell programs in collaboration with fuel cell manufacturers. Fuel cell developers were mostly focused on development of stacks and stack components. Carmakers generally focused more on system design and complementary technologies required for an operational fuel cell system for car application.

---

[36] Between 1990 and 1996 there have been discussions in other states (Massachusetts, Vermont, New York State) that considered to adopt the Californian ZEV regulation, thereby posing a threat to the car industry that the ZEV guideline would become a standard US wide.

[37] In case hydrogen is produced in a sustainable way.

Further stakeholders include national governments and programs on EU level, supporting research, development and demonstration of fuel cell vehicles.

R&D (industry and government)

R&D programs of fuel cell manufacturers are largely sponsored in national subsidy programs, with a focus on increasing stack performance, (application oriented) system design and demonstration of working prototypes. Research is supported and catalyzed by the car industry, which is one of the biggest sponsors of fuel cell programs. By 1996 all prominent carmakers had extensive fuel cell programs, and were developing or had demonstrated a prototype fuel cell vehicle (Van den Hoed, 2004).

R&D programs tend to show technical diversity in the design of fuel cell vehicles, in terms of (i) fuel, (ii) type of fuel cell, (iii) level of hybridization. For fueling the majority of R&D programs is focused on hydrogen (both gaseous as well as liquefied), while also methanol as energy carrier is investigated. PEM fuel cells are used in most R&D programs, but also alkaline fuel cell (AFC) and in a later stage solid oxide fuel cell (SOFC) prototypes are developed.

Demonstration projects

R&D programs were mainly focused on developing working prototypes in order to evaluate suitability of fuel cells in cars. The first fuel cell prototype is shown by Ballard in 1991 that applied fuel cells in a bus (1991). The first automotive fuel cell prototype is demonstrated by Daimler-Benz in 1994 (NECAR I) and 1996 (NECAR II), followed by Toyota (1996) and Honda (1996). Weight, volume and costs provided major barriers, although the progress made by Daimler-Benz (NECAR I to NECAR II) was sufficiently significant to scale up R&D activities in fuel cell vehicles.

Policy

No specific policies were in place for fuel cell vehicles. Most policies concerning emissions and energy efficiency were 'technology-neutral', allowing carmakers to achieve the standards with the technology they preferred. The zero emission regulation in California stands out in the sense that zero emission was unreachable for conventional ICE cars. Given that in the early 1990s electric vehicles were the only realistic option to achieve zero emissions, this regulation has received critics for being a program specifically focused on stimulating electric vehicles. In this period R&D activities in fuel cell technology provided carmakers with another alternative.

Period 1997–2001 - Fueling fuel cell vehicles -

Visions

The demonstrations of prototypes as well as the progress made in its performance resulted in an increased belief that fuel cell technology had perspectives for commercial automotive applications. Illustrative is the historical power density curve of Ballard, showing increases of power density (an important characteristic of fuel cells) of a factor 10 in less than five years (Figure27).

In 1998, Daimler-Benz announced that it expected to have 40.000 fuel cell vehicles on the road in 2004[38]. General Motors' ambitions were to be the first carmaker to put 1 million fuel cell vehicles on the road[39]. In Japan the Ministry of Economy and Trade (METI) set the target on having 50.000 fuel cell vehicles on the road by 2010, and 5 million by 2020 (METI 2001). With these ambitions the issue of fueling fuel cell vehicles becomes a major priority.

The improved perspectives for fuel cell vehicles come together with a decline in interest in its competitor, the battery electric vehicle. Although most carmakers had one or several electric models for sale, the market for electric vehicles proved to be limited (Van den Hoed 2004). Fuel cell technology provided a more attractive alternative in terms of size/weight, power and refueling. As a result, the vision on electric vehicles shifted from battery driven to fuel cell driven.

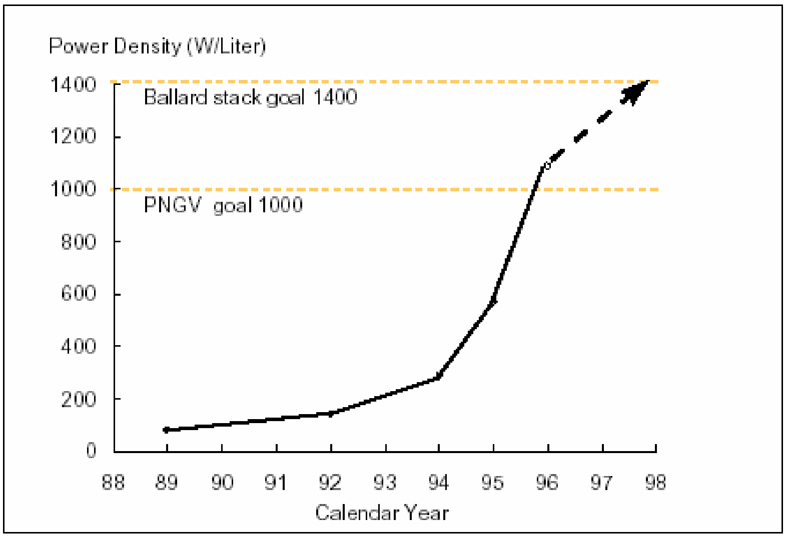


Figure 27: Power density development of Ballard's fuel cell stack (Kalhammer 1998)

38 Press release Daimler Chrysler 1998.
39 Press release General Motors 1999.

Stakeholders/actors

Most prominent stakeholders in the development of fuel cell vehicles remained the car industry. By 2001 all major carmakers had extensive R&D programs, mostly linked to programs of individual fuel cell manufacturers[40]. The number of fuel cell manufacturers increased significantly in this period, as well as companies with complementary activities for instance in hydrogen storage technology, high power electronics, hydrogen handling and refueling technology. Similarly, suppliers for the fuel cell stack itself become increasingly involved, such as the chemical industry (membranes, catalysts). Within this period a ‘fuel cell industry’ is in preparation with specialized suppliers of relevant components in the complete fuel cell drive train.

Relevant with respect to fuels and infrastructure was the entrance of the oil industry in the fuel cell technology. Governments on national and transnational level become increasingly involved in providing funding for R&D activities with respect to fuel cell vehicles through increasingly extensive subsidy programs. Lastly large technological institutes are heavily involved in fundamental research activities.

R&D

R&D activities in this period increased rapidly, with a focus on stack development, balance of plant issues of the fuel cell system, storage technology, and hydrogen handling (Kalhammer 1998). Both more fundamental research as well as application oriented research is carried out. Fundamental research is focused on developing alternative catalysts, membranes and storage technologies (e.g. metalhydrides, nanotubes), and is more carried out by large technological institutes and fuel cell manufacturers.

More application oriented research resides in R&D labs of carmakers and fuel cell manufacturers. Ambitious targets are set in which respect to amongst others costs, power density, start up time, efficiency (see figure 28). R&D activities are focused on evaluating the commercial perspectives of fuel cells in the automotive industry. Both fundamental and application oriented design found large subsidy support in national programs as well as in EU, DOE and METI programs.

Relevant for this study are the R&D activities related to fuel and infrastructure. Between 1997 and 2002 several competing fuels are pursued: methanol (via reformer), gasoline (via reformer) and direct hydrogen. An intermediary step (methanol, gasoline) towards a large scale hydrogen infrastructure is envisaged given that infrastructure costs for these liquid fuels are significantly lower than for (gaseous) hydrogen. In turn this has lead to large scale investments by the car industry in reforming technology (Kalhammer 1998, Van den Hoed 2004).

[40] Fuel cell manufacturers were largely dependent on funding from automotive programs, while by investing in fuel cell manufacturers, carmakers gained access to valuable knowledge in this technology.

The majority of the industry favored fuel cell technology to achieve zero emission. Only BMW focused its activities on developing hydrogen fueled ICE vehicles. This is partly explained by the fact that BMW was not affected by the ZEV regulation and partly by more cultural aspects within BMW (more engineering focused, strong attachment to ICE)[41].

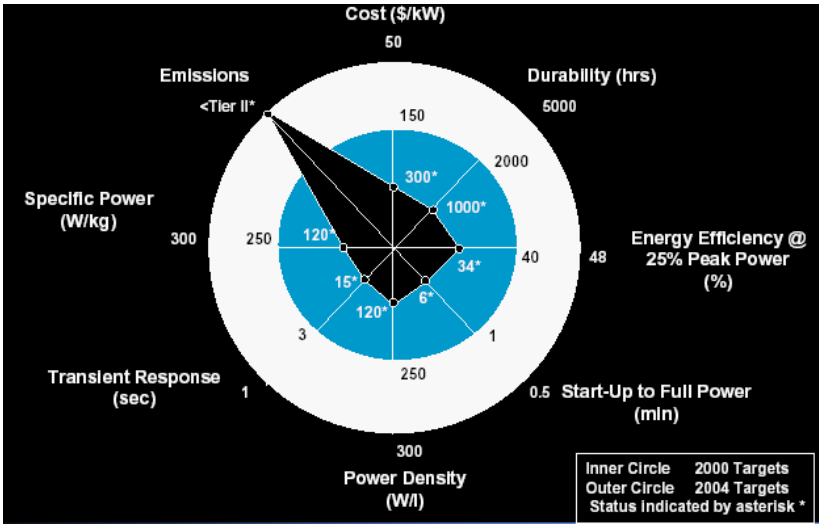


Figure 28: Performance objectives and current status of a gasoline-fueled FCV (situation in 2000)[42]

Demonstrations

By 2002 more than 50 demonstration vehicles with fuel cells were shown by the car industry as well as by large technological institutes and fuel cell manufacturers (Figure29). Mostly these included passenger cars and buses. Given the multi-functionality of fuel cell technology, demonstrations of fuel cells in small mobile applications, combined heat and power and electronic applications are shown.

[41] See for a deeper elaboration on strategies of automotive companies with respect to hydrogen and fuel cells in Van den Hoed (2004)

[42] http://www.ott.doe.gov/pdfs/01-miliken.pdf

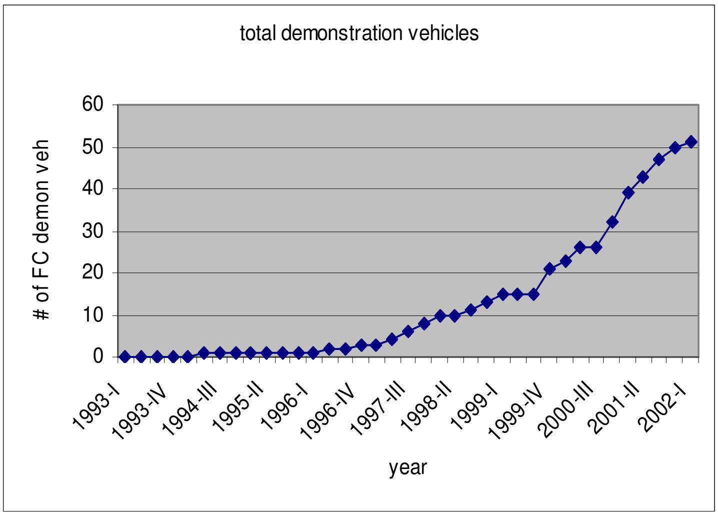


Figure 29: Number of demonstration vehicles 1994-2002 (Van den Hoed, 2004)

Policy

Throughout 1996 and 2001 a range of changes occurred in the Zero Emission regulation in California (CARB 1996; CARB 1998; CARB 2001). The percentage required for carmakers was reduced from 10% to 2% in 2003. The reduction was compensated by sales quota on alternative drive systems such as hybrid vehicles, natural gas vehicles and fuel cell vehicles on methanol[43].

Optimized combustion engines are able to achieve emission standards set in Europe (Euro IV and Euro V). Similarly the voluntary agreement concerning CO_2 reduction targets (120 gr/km in 2010) between the ACEA[44] and the EU form a weak incentive to develop CO_2-low alternatives, given optimization opportunities of ICEs (e.g. hybridization).

Apart from standard setting, policies are largely focused on funding R&D activities in fuel cell technology and providing opportunities to develop demonstrations of fuel cell vehicles and hydrogen tank stations.

Period 2002–2006 - Towards commercialization-

The period 2002-2006 can be characterized as a period in which commercialization is pursued of the fuel cell vehicle, by further bringing down costs and setting up larger scale demonstration projects.

[43] Although methanol fueled fuel cell vehicles are not zero emission. The measure is meant to stimulate the sales of fuel cell vehicles, with methanol as an intermediary fuel.
[44] European branche organization for car manufacturers.

Visions

Small scale demonstration projects in the preceding period have demonstrated the technological performance of fuel cell technology for car applications. Therefore by 2002, the technical viability of fuel cell vehicles is hardly a point of debate – increasingly there is a belief that fuel cell vehicles may be a viable commercial option in the long run.

The progress in fuel cell technology catalyzes the discussion on a future 'hydrogen economy'. Illustrative is the influential publication of Rifkin's "The Hydrogen Economy: The creation of a world wide energy web and the redistribution of power" (Rifkin 2002). Although the automotive sector received a great deal of attention for developing fuel cell vehicles, the hydrogen economy takes the application of fuel cells and hydrogen broader as a technology that may become dominant in our future (sustainable) energy household.

Despite the visions of a long term hydrogen economy, critics concerning the environmental, economic and to a lesser extent safety aspects of hydrogen and fuel cells are heard. Hydrogen chain efficiencies are not as favorable as expected and may be in line with future hybrid vehicles (Weiss; 2003). Furthermore, costs of fuel cells are prohibitive, illustrated by the US $ 1M demonstration vehicles presented by Toyota and Honda in December 2002.

Despite these question marks and critiques, the long-term picture of fuel cell vehicles and hydrogen (generated by photovoltaic or wind) remains a strong vision that continues to support and fuel R&D activities and demonstrations with fuel cell technology.

Stakeholders/actors

The automotive industry remains the largest sponsor of the fuel cell industry. In this period an increasing role of the oil industry can be seen (setting up infrastructure) as well as the gas industry (delivery of hydrogen). With fuel cell technology getting closer to commercialization, a growing industry of (component) suppliers and complementary technologies can be observed (e.g. storage technology, gas detection systems). Lastly, on all governmental levels hydrogen programs can be observed that support the development of fuel cell technology and endeavor to attract fuel cell related companies to stimulate economic development.

Within the automotive and oil industry, new partnerships can be observed (see figure 30). The linkages (also with fuel cell manufacturers) illustrate the need to join forces, and create strong alliances in order to actively influence technology decisions within the industry (Van den Hoed 2004).

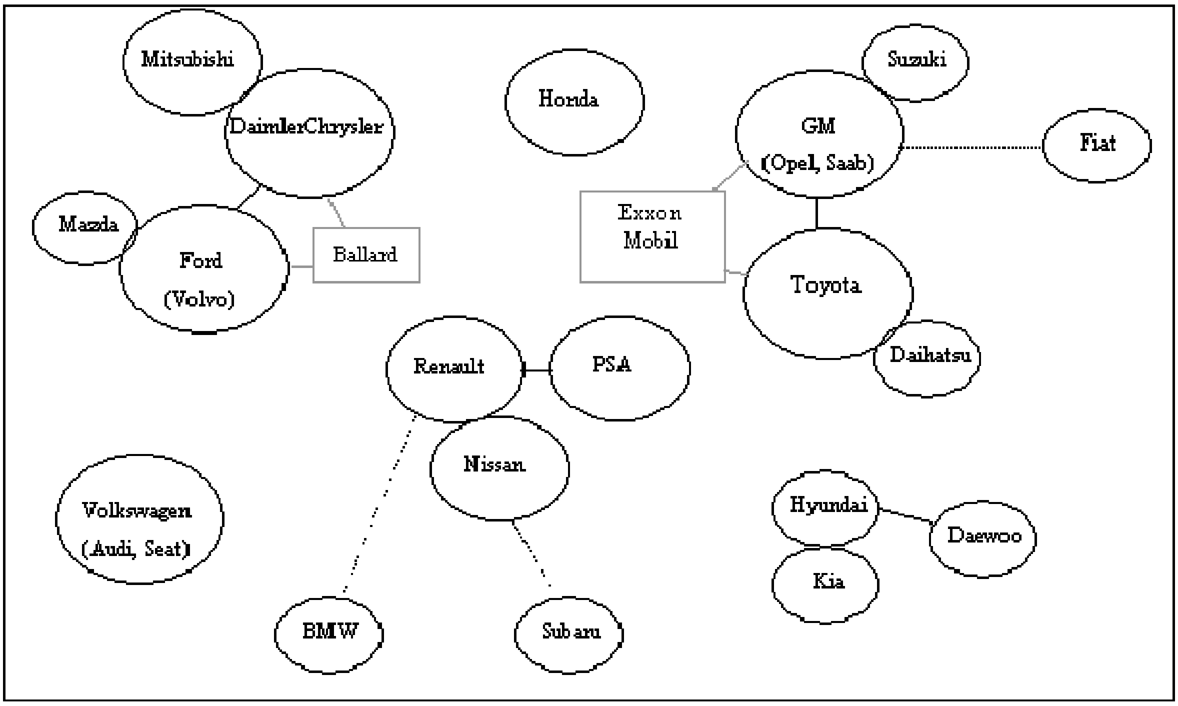


Figure 30: Collaboration and competition between carmakers in fuel cell technology (situation July 2003). The size of the circles corresponds roughly to the size of the firm (in terms of sales). The dotted lines reflect R&D collaborations.

R&D activities

R&D activities continue to become more application oriented, and move from research to development. Furthermore, large firms like Toyota, GM, DaimlerChrysler and Honda further substantiate their FC-efforts, with programs of up to 300-600 staff, with annual investments of US $ 200-400M[45]. Furthermore, large R&D programs are supported by the EU, the US and Japan, in which apart from the automotive industry large technological institutes, universities and fuel cell technology related firms reside.

R&D topics tend to shift in this period, for instance regarding preferred fuel. Whereas in the late 1990s a competition between methanol and gasoline as the preferred intermediate fuel for fuel cells occurred, by 2004-2005 a general consensus within the oil and automotive industry was reached that hydrogen should directly be the preferred fuel. Press releases from oil companies suggest their increased commitment to setting up a hydrogen infrastructure (e.g.. Shell, BP).

[45] Based on company statements, see for an overview Van den Hoed 2004.

Demonstrations

A great deal of (increasingly larger scale) demonstration projects can be discerned in this period. Illustrations include:

- CUTE project. An EU sponsored program in which 30 fuel cell buses on hydrogen are operated in ten European cities (2003-ongoing). Among the test locations is Amsterdam, and Iceland.
- DaimlerChrysler demonstrates fuel cell Sprinter buses in collaboration with Hermes Versand Service (2001-2003).
- In California the Californian Fuel Cell Partnership (CFCP) has the objective to stimulate fuel cell vehicle deployment. With nearly all automotive and oil companies as partners, a roadmap to a hydrogen highway is developed in which a particular highway has several tank stations for hydrogen.
- The first fuel cell vehicles to be commercially leased to customers were presented in Tokyo in December 2002. Toyota and Honda both deliver six fuel cell vehicle-models, to be used by research institutes and agencies in the US and Japan.

By 2006 more than 60 hydrogen fueling stations are available worldwide, the majority in the US, Japan and to lesser extent in Germany[46]. Several hundreds of fuel cell vehicles have been demonstrated and are in the process of being tested. The tests provide large scale data for analysis of the further proof of concept and economic viability of the fuel cell vehicle.

Policy

Whereas technology is developing, stringent policies tend to diminish. By 2005, the CARB regulation has been delayed and watered down to the extent that carmakers have several flexible options to meet (close to) zero emission levels.

By 2006, car manufacturers are facing challenging regulations in terms of alternative fuels and bio fuel adoption[47]. Hard targets are set for bio fuel in the short term. In the White Paper for transportation, hydrogen is mentioned as a future technology, rather as a short term solution. And thus, no hard targets are set for the automotive industry; policy is mostly focused on supporting R&D projects for successful development of commercially attractive fuel cell vehicles.

[46] www.fuelcells.org
[47] Biofuel directive 2003/96

Conclusions transition process of fuel cell vehicles

In the period 1990 to 2006, the interest in fuel cell vehicles has demonstrated a steady increase, in terms of industry investments, policy involvement and support, stakeholders, R&D activities and demonstration shown. Understanding the factors that lead to this increase in activity in this potential influential technology option is a very complex process.

As Van den Hoed (2004) argues, an important condition for success has been the ZEV regulation in California (1990) that stimulated carmakers to look for zero emission alternatives. Basic R&D (Ballard, Daimler) has been an important factor to identify the potential of fuel cells, and improve its performance level. Demonstrators have played a role in demonstrating technological viability and convince other stakeholders to engage. Competition between carmakers, attempts of the car industry to improve their image, staggering oil prices, have all played a role in the increased activities in fuel cell vehicles. As a result the industry is self-propelling, with an increasing amount of stakeholders and investors entering. Without major market breakthroughs, it is questionable how long this effect may continue.

Table 11: Summarizing events in development of Fuel Cell Vehicles

Period	Stakeholders	Technology	R&D	Demonstration projects	Policy
Before 1990 Alternative fuel cell applications	Fuel cell manufacturers, national governments, EU.	Fuel cells for space applications	Research	None	
1990-1996 Exploring perspectives of fuel cell vehicles	Fuel cell manufacturers, carmakers, national governments, EU.	Fuel cell vehicle. Fuel: hydrogen	Focus on technical viability and demonstration (Research)	Several prototypes (<10)	Zero emission regulation
1997-2001 Fueling Fuel Cell Vehicles	Idem + oil industry, suppliers fuel cell manufacturers.	Several FCV-design configure. Fuel: gasoline/ methanol/ hydrogen	Focus on cost reductions in stack, storage, reformers (research and development).	Large number of prototypes by carmakers and FC mfrs (>50). Passenger cars and buses.	Zero emission regulation + Influence Kyoto protocol

Period	Stakeholders	Technology	R&D	Demonstration projects	Policy
2002-2006 Towards commercialization	Idem + evolving fuel cell industry (complete supply chain) + differentiated end-users	Fuel cell vehicle (hybrid) Fuel: hydrogen	Focus on mass-manufacturers + focus on complementary technologies (balance of plant) (development)	Large number of prototypes (>100) and sold vehicles (>100).	Zero emission regulation + CO_2 regulations + local emission regulations + alternative fuel policies.

Historical development CSP for fuel cell vehicles

Today's most advanced renewable technology to produce hydrogen through a non-electrolysis way is based on biomass. However, laboratory investigations and theoretical studies have already shown that also CSP could be used through thermo chemical reactions to produce hydrogen. This route is one of the novel applications that is being researched.

The first European research project on this topic has been the Hydrosol project that started in 2002 (European Communities, 2005). One of the main challenges was to develop a catalyst system suitable for water dissociation and at the same time regeneration of this catalyst. Under the sixth Framework Program (FP6) 2002-2006, two more projects in this field were funded: Hydrosol II and SOLHYCARB. At the moment there are no such plants in commercial operation.

The system option CSP for hydrogen in fuel cell vehicles as a novel application to produce zero emission transport fuels gains more attention these years. Although for both technologies no commercial market exists yet, its future outlook is optimistic. One of the only studies that deals with both aspects of solar thermal hydrogen production and end use in fuel cell vehicles is from A. Meier and R. Felder. It gives a life cycle analysis of hydrogen utilization in fuel cell vehicles compared to advanced gasoline and diesel power trains, concluding that hydrogen production through Zn/ZnO may hold promise for future hydrogen fuel cell vehicles.

Apart from this publication and reports links between CSP and fuel cell vehicles have been limited.

Conclusions

This study provides an assessment of the perspectives of CSP in the production of hydrogen as a fuel for fuel cell powered transportation. It includes a second-opinion of a leading study on the perspectives of solar thermal power (NREL 2003). It sketches three most likely routes from CSP to fuel cell vehicles in Western Europe and compares them to two reference cases. Finally a transition evaluation is made of CSP and fuel cell vehicles with the objective to identify policy opportunities for stimulating long term transition changes.

What are the perspectives of CSP?
In general it can be said that CSP has promising perspectives to generate a vast amount of sustainable electricity in the future. Experience with field tests of plants developed in the 1980s have been, and still are successful. Currently an upheaval in the interest to set up CSP plants can be observed, leading to further learning and scale effects. The most likely locations for CSP are North Africa and Southern Europe (Spain).

To what extent are the cost projections of the NREL study realistic?
Based on an analysis of available literature and supported by the expertise of partner DLR, the estimates of the NREL study (2003) concerning future electricity costs (5,5-6,2 €cts/kWh) from CSP are found realistic. The projections are based on real-life experiences with available CSP technology in the US. The deployment rates of CSP assumed by NREL are in line with the current attention for realizing CSP installations in Spain and North Africa (e.g. Morocco, Egypt).

What are the most likely chains from CSP produced on location, to hydrogen as a motor fuel in Western Europe?
Based on an analysis of individual chain elements, three most likely CSP to fuel cell vehicle chains have been assessed:

1. **GH2 route** Transporting gaseous hydrogen (GH2) per pipeline to Western Europe, and using a hydrogen infrastructure to individual end-users to allow hydrogen home fueling.
2. **LH2 route** Transporting liquefied hydrogen (LH2) per ship to Western Europe, and distributing it to refilling stations per tube trailer.

3. **HVDC route**: Transporting electricity generated by CSP per high voltage DC (HVDC) lines to Western Europe, and distribution to refilling stations to generate hydrogen on site via electrolysis. The HVDC can be a backbone for a sustainable energy infrastructure, in which also other sustainable sources can be plugged into.

How do the CSP chains compare with the reference case on a well-to-wheel basis?
The CSP routes have been compared with (A) a gasoline internal combustion engine (gasoline ICEV) and (B) a plug in hybrid on bio fuels (PHEV bio-fuel).

In a multi-criteria evaluation, CSP routes prove to be an attractive alternative for the gasoline ICEV in terms of well-to-wheel efficiency (factor 1,5-2 more efficient), GHG emissions (70-95% reduction) and local emissions (NOx, CO). Furthermore, land use requirements will not necessarily be much higher than the conventional oil and gas route. Between the CSP routes, the GH2 suffers from low efficiencies and GHG emissions of the home fueler (compressor) – in case distribution to gas stations is taken into account, the GH2 has similar efficiencies and environmental advantages as the other CSP routes.

Cost prices of hydrogen from CSP will be a factor 2,5 to 5 higher than conventional gasoline per distance traveled. It should be noted that CO_2 costs where not taken into account; similarly variation in oil prices was limited to 25-50$/bbl. Higher prices are a result of conversion steps and intrinsically higher prices for CSP compared to conventional oil. Transport is a relatively small factor (10-20% of the total cost price).

The PHEV route illustrates how storing CSP electricity directly into a battery (in the car) reduces GHG emissions and costs (even compared to the gasoline route) and increases efficiency. Conversion steps are avoided, while this route demonstrates the advantages of electric vehicles over fuel cell vehicles in overall well-to-wheel efficiency. A negative aspect of the PHEV-bio fuel is the land use (factor 15-20 higher than CSP).

Which factors help explain the transition development of CSP in the period 1990-2006?
The description of the CSP and fuel cell vehicle cases show how interest in a technology can accelerate and decline, in terms of involved community of stakeholders, scale of investments, scale of supporting programs, R&D programs and number of demonstration projects.

Regarding the upheaval and decline in interest of CSP, the following factors were found to influence this process.

- High **oil prices** have provided an important context factor for investments in CSP, explaining at least part of the ups and downs of CSP. However, oil prices alone cannot explain the case of CSP.
- **Supporting measures** such as feed-in tariffs provide a powerful explanation for the current interest in CSP by Spanish organizations. Similarly the North-African projects are largely profiting from attractive subsidy/financing schemes.
- **Demonstrations** have been relevant in providing practical data (data we currently use to justify low cost projections), and provide a proof of principle from a technical and economic point of view. Demonstrators have fueled the visions for investors, industry as well as policy makers.
- **R&D projects** have been important factors to build up further knowledge regarding CSP. Large subsidy schemes in the US and Europe have been instrumental in bringing knowledge forward to further bring CSP closer to commercialization.

The case of fuel cell vehicles is different from CSP in terms of investments, type of industry involved and political power behind the developments. Important explaining factors for the rise in fuel cell vehicles include the **stringent regulation** (California), **competition** between car manufacturers and anticipation of high/dynamic **oil prices** have played a role, although more skeptical views include **public relation** motives. Nevertheless, the fuel cell vehicle case shows how the industry has become self-propelling with a large number of stakeholders and investors, although large scale commercial projects have been limited so far.

Perspectives for the Netherland and policy recommendations

The renewed interest in the Netherlands for CSP has lead to differing views on the role the Netherlands should and could play in this technology. The case descriptions show the involvement of German knowledge institutes, private companies and policy makers in the development of (knowledge around) CSP.

With the increased interest in CSP, the question can be asked if and how the Dutch government can play a role in CSP development, and how this may contribute to the Dutch policy objectives and industrial activities. Although the above question has not been object of this study, the following opportunities may be highlighted regarding Dutch involvement in CSP, based on the case study descriptions.

- Linkages with **Dutch climate policy**. A this moment is the extent to which CSP project qualify as CDM/JI projects is unclear. CSP may fulfill part of the climate policy objectives of the Dutch government (e.g. in terms of effectiveness, cost efficiency).
- Linkages with **policies for developing countries**. CSP may significantly contribute to self sufficiency of developing countries, while desalination of sea water may provide clean water in parallel. Development of CSP is in line with, and could benefit from objectives of (Dutch) foreign policies for developing countries.
- Reduce dependence on **geopolitical sensitive regions**. By investing in CSP, the Netherlands may open opportunities of importing CSP on the long term. The extent to which this is possible, and the time frame by which CSP may contribute to a Dutch energy portfolio requires further study.
- Opportunities for **Dutch CSP industry**. The study shows how no dominant designs have emerged in the field of CSP and that technological advancements continue. Furthermore, the study shows that the industry in CSP is still growing, and that with the expected growth it is likely that there will be room for new industrial parties in this field. Although not a topic of study in this report, it is not unrealistic that Dutch industry may play a role in the commercialization of CSP, be it as a project developer, operator, supplier of components, or a knowledge institute with innovative designs.

Given the increased perspectives of installations to be built, particularly in Spain and North Africa, it is recommended to further study above synergies with Dutch policies and economic opportunities.

References

Aringhoff, R., Brakmann, G., Geyer, M., Teske, S. (2005): Concentrating Solar Thermal Power-Now. Greenpeace, ESTIA, IEA SolarPaces.

Bossel U. (2005): On the Way to a Sustainable Energy Future. European Fuel Cell Forum 2005.

CARB (1996): Staff Report: Final Statement of Rulemaking; Amendments to the Zero Emission Vehicle Requirements for Passenger Cars and Light Duty Trucks. Sacramento, CA: California Air Resources Board.

CARB (1998): Proposed Amendments to California Exhaust, Evaporative and Refueling Emissions Standards and Test Procedures for Passenger Cars, Light-Duty Trucks and Medium-Duty Vehicles-LEVII: Sacramento, CA: California Air Resources Board.

CARB (2001): Zero Emission Vehicle Program Changes: ARB Fact Sheet. Sacramento, CA: California Air Resources Board.

CARB (2003): Staff Report: Initial Statement of Reasons; 2003 Proposed Amendments to the California Zero Emission Vehicle Program Regulations. Sacramento, CA: California Air Resources Board.

Cooper, A. Cheng, H. and Pez, G. (2006): Hydrogen storage by reversible hydrogenation of liquid-phase hydrogen carriers. May 2006.

De Vries, B., M. Hoogwijk and D. van Vuuren (2006): Renewable energy sources: Their global potential for the first half of the 21st century at a global level: an integrated approach. Submitted to Energy Policy, 2006.

DLR - German Aerospace Center, (2005): CSPfor the Mediterranean Region. Commissioned by: Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, Germany. Final Report, Chapter 7 Environmental Impacts of MED-CSP Scenario, pp 159-174

DLR - Deutsches Zentrum für Luft- und Raumfahrt e.V., WI - Wuppertal Institut für Klima, Umwelt und Energie, FhG-ISE - Fraunhofer Institut für Solare Energiesysteme (2003): SOKRATES Projekt - Arbeitspaket 1: Finanzierungs-instrumente für die Markteinführung solarthermischer Kraftwerke - Das Szenariomodell ATHENE, 2. überarbeiteter Entwurf, www.me.kp.dlr.de/tt/institut/abteilungen/system/publications/ATHENE-03.pdf.

Drolet B. and Gretz J. (2002): The Euro-Québec Hydro-Hydrogen Pilot Project; The beginning of the industrialization of hydrogen.

Edwards, R. et al. (2005): Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains. European Commission, Concawe, Eucar (2^{nd} version).

Eichhammer, Wolfgang et al. (2005): Assessment of the World Bank / GEF Strategy for the Market Developing of Concentrating Solar Thermal Power. Fraunhofer Institute ISI and ISE, CSIRO and CSIR.

Energy Advisory Council (2006): Letter of advice on Concentrating Solar Power (CSP). The Hague, 3 March 2006.

European Commission (1997): Energy for the Future: Renewable Sources of Energy, a White paper for a Community Strategy and Action Plan. COM(97) 599 Final.

European Commission, (2004): European Research on Concentrating Solar Thermal Energy. Project Synopses. Directorate-General for Researc, Brussels, Belgium.

Faist M, N. Jungbluth, T. Heck (2003): Erdgas [Natural gas]. In: Dones R, editor. ecoinvent report No. 6. Swiss Centre for Life Cycle Inventories, Dübendorf, CH.

Federal Ministry of Economics and Labour (2005): Innovation and new energy technologies. The 5^{th} Energy Research Program of the Federal Government, Berlin, July 2005.

General Motors, ANL, BP, ExxonMobil and Shell. (2001): Well-to-Wheel Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems - North American Analysis-. Detroit.

Greenpeace International (2005): Concentrating Solar Power – Now! Greenpeace, ESTIA, IEA SolarPACES Implementing Agreement.

Hamelinck CN and Hoogwijk M (2006): Future scenarios for first and second generation biofuels (forthcoming), Ecofys, Utrecht, the Netherlands.

Hoed, R. van den (2004): Driving Fuel Cell Vehicles; How established industries react to radical technologies, Dissertation, Tan Heck, Delft, the Netherlands.

Hofman, Y, D. de Jager, E. Molenbroek, F. Schillig, M. Voogt (2002): The potential of solar electricity to reduce CO_2 emissions. By order of the IEA Greenhouse Gas R&D program, Ecofys, Utrecht, The Netherlands.

IEA/OECD (2005): Prospects for Hydrogen and Fuel Cells; Energy Technology Analysis, Paris, France.

IEA/OECD (2004): Cedric Philibert, International Energy Agency, International energy technology collaboration and climate change mitigation. Case Study 1: Concentrating Solar Power Technologies. COM/ENV/EPOC/IEA/SLT(2004)8.

Kalhammer, F.R., Prokopius, P.R., Roan, V.P. and Voecks, G.E. (1998): Status and Prospects of Fuel Cells as Automobile Engines: A Report of the Fuel Cell Technical Advisory Panel. Sacramento, CA: Prepared for the State of California Air Resources Board.

Kabariti, M. et al (2003): Trans Mediterranean Renewable Energy Cooperation “TREC” 2003 for development, climate stabilization and good neighborhood.

Koppel, T. (1999): Powering the Future: The Ballard Fuel Cell and the Race to Change the World. New York: Wiley.

Kreith, F., R.E. West (eds.) (1997),:CRC Handbook of Energy Efficiency. Chapter 21A: Solar Thermal Power and Industrial Heat: Solar Thermal Power. CRC Press.

Lako, P., de Vries, H.J. (2006): Stand van de techniek van elektriciteitsopwekking op basis van zonthermische centrales. ECN rapport C-05-087.

L-B Systemtechnik (2006), Assumptions, visions and robust conclusions from project Phase I, Ottobrun

Lubbers, P. (2006): Personal communication on Wednesday 19 July 2006

Lysen, E., S. van Egmond, et al (2005): Verdieping Transitiepaden. In opdracht van het Ministerie van Economische Zaken, 1-3664.

Mazza, P. and R. Hammerschlag, (2004):Carrying the Energy Future; comparing hydrogen and electricity for transmission, storage and transportation. Institute for Lifecycle Environmental Assessment. www.ilea.org.

METI (2001): Report of the Fuel Cell Commercialization Policy Group

Müller-Steinhagen, H, Trieb (2004): F. Concentrating solar power, A review of the technology, part 1.

Müller-Steinhagen, H, Trieb, F. (2004) Concentrating solar power, A review of the technology, part 2.

NAE (2004): The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs, National Academy of Engineering

Niedzwiecki A. (Quantum Technologies): Storage. Proceedings Hydrogen Vision Meeting, US DOE, Washington, 15-16 November 2001. (http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/hv_report_12-17.pdf).

Nitsch, J and M. Fischedick (2002): Eine vollständig regenerative Energieversorgung mit Wasserstoff –Illusion oder realistische Perspektive? 2002.

Ogden J. and C. Yang 2005: Implementing a Hydrogen Energy: Infrastructure: Storage Options and System Design. http://repositories.cdlib.org/cgi/viewcontent.cgi?article=1121&context=itsdavis

Pitz-Paal, R., J. Dersch, B. Milow (2005): ECOSTAR (European Concentrating Solar Thermal Road-Mapping) Roadmap document, Deutsches Zentrum für Luft- und Raumfahrt e.V., SES6-CT-2003-502578, ftp://ftp.dlr.de/ecostar.

Ragwitz, M., M. Wietschel, U. Hasenauer, O. Fakolade (2003), ASTEEM ESTO Study; Introduction of Alternative transport Fuels in the European Energy Market: Techno-Economic barriers and Perspectives. Workpackage: Hydrogen, Karlsruhe

Renewable Energy World (2001): Small hydro – policy and potential in Spain, p. 151, September/October 2001

Rifkin, J. (2002): The Hydrogen Economy the Creation of the World-Wide Energy Web and the Redistribution of Power on Earth: Tarcher/Putnam.

Ros, J., J. Farla, J. Montfoort, D. Nagelhout, M. Reudink, T. Rood, H. van Zeijts, (2006): Evalution methodology for NMP-4 transitions. Set up for the evaluation of the policy supporting system innovations on the long term. Netherlands Environmental Assessment Agency, January 2006.

Sargent & Lundy (2003): "Assessment of Parabolic Trough and Power Tower Solar Technology Cost and Performance Forecasts" SL-5641, Chicago, IL, USA, May 2003.

Holland Solar (2005), Transitiepad zonnestroom; De Roadmap van Holland Solar, Utrecht

Schaeffer, G. J. (1998): Fuel Cells for the Future; A Contribution to Technology Forecasting from a Technology Dynamics Perspective. Dissertation. Petten, Netherlands.

Schultz, K.R. (2003): Use of modular helium reactor for hydrogen production. Annual symposium 2003 of the World Nuclear Association.

Trieb. F, (2006-1): Trans-Mediterranean Interconnection for concentrating solar power. Report DLR April 2006

Trieb, F, (2006-2): Trans-Mediterranean Interconnection for Concentrating Solar Power. DLR Brochure 2006.

Weindorf, W., U. Buenger and J. Schindler (2003): Comments to the paper by Baldur Eliasson and Ulf Bossel, The future of the hydrogen economy; bright or bleak?".

Weinrebe, G., M. Böhnke, F. Trieb (1998): Life cycle assessment of an 80 MW SEGS plant and a 30MW Phoebus Power tower, ASES conference, Albuquerque.

Weiss, M. A., Heywood, J.B., Schafer, A. and Natarajan, V.K. (2003): Comparative Assessment of Fuel cell vehicles (No. MIT LFEE 2003-001 RP). Boston, MA: Massachusetts Institute of Technology.

Wenzlawski, H. (2003): The Global CSP Market – Its industry, structure and decision mechanisms. Master Thesis, Hamburg University, Germany.

Relevant websites:
www.SOLARPACES.org
www.earthscan.co.uk
www.CSIRO.au
www.det.CSIRO.au
www.ilea.org

Appendix 1: Other hydrogen production

Various energy sources and carriers can be applied and converted into hydrogen using chemical, physical and biological reactions. These have been summarized in Appendix 1 in A "Current" and B "Future options".

A Current options:

Gas reactions from fossil fuels. Natural gas is the main hydrogen source these days. The conversion takes place through chemical reactions in the gas phase. Different chemical processes can be applied. The most efficient is currently the combination of the water reforming reaction (to H2 and CO), followed by the shift reaction (to H2 and CO_2).
After gasification coal can become a major source to produce hydrogen in the future.
These fossil energy sources require the development of optimal CO_2 capture and sequestration technologies in order to meet the requirements for sustainable use in respect to the influencing global climate.

Biomass can be applied to produce hydrogen in various ways. Biomass gasification processes include thermo-chemical and biological processes. Amongst others, the choice of processes depend on the water content of the biomass, if applicable avoiding the evaporation energy of water. After gasification, capture and storage of CO_2 might be considered to obtain a negative CO_2 balance! Biological processes often are related to waste treatment.
Wet biomass is usually treated differently, to avoid the costs for evaporation of the water. In that case, either a hydrothermal process can be applied or, biological processes may be considered, especially in diluted waste streams.

B Future options

Thermo-chemical cycles involve direct high-temperature conversion that net produce hydrogen and oxygen. The high temperatures can be generated by solar energy.

Different complex thermo chemical cycles have expected hydrogen production efficiencies in the range of 40-50%. These cycles are however in an early state of development and include, intensive corrosion problems to be tackled. This high potential technology seems to attract more attention. This is partially related to an thermal energy source from high-temperature nuclear reactions.

One example is the Sulphur-Iodine cycle (SI-cycle). Eventually, via a complex set of reactions at different temperatures, hydrogen and oxygen is produced by splitting water. The high-temperature heat used may be as high as at 1100 ˚C. Depending on the applied temperatures, the estimated efficiencies of the process have been estimated quite high (43% at 900˚C).

<u>Photo Electrolytic Conversion; PEC</u>

Secondly, a special PV type of system (PEC) could be considered for hydrogen production. This is not a thermal method like the CSP systems, but it is based on PV and the ability to use diffuse light in moderate temperature regions. To explain the difference it is necessary to distinguish the principles of the:

- Photo Voltaic conversion (PV) and
- Photo Electrolytic Conversion (PEC)

Photo Voltaic conversion; PV is the generally known solar-to-electricity process. Lowering the cost of the cells and increase their efficiency has made great steps in the recent years. However the use in the production of hydrogen appears not (yet?) realistic as the cost of electricity of PV is still quite high. Figure 6-1 shows the development of the price of PV electricity as expected by Holland Solar (2005).

The diagram indicates the current cost of about 0.40 €/kWh which becomes competitive in approximately 2020, when it is expected to equal the cost about of conventional electricity; 0.20 €/kWh, to become more economic next years[48]. Obviously, the cost of this electricity is too high for hydrogen production in transportation as the cycle through electrolyser has both economic and efficiency cost.

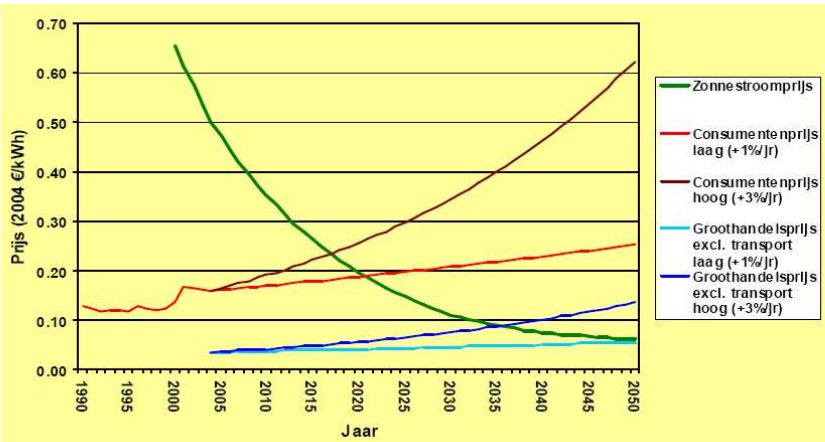


Figure I: Cost of electricity of Solar PV (green line) and different cost scenarios for conventional electricity (Holland Solar, 2005)

[48] Cost reductions are based on historically shown cost reductions as a result of increase production scale (23% cost reductions with doubled production scale (Holland Solar 2005).

Photo Electrolytic Conversion (PEC) PEC produces no electricity. This special type of PV ("tandem-cell" design) is able to directly produce hydrogen from light (so without the electricity step) also using diffuse solar light. The concept is based on the decomposition of water due to the excess potential of the so-called 'tandem cells'.

This technology is in the R&D phase. But, recent results appear quite promising. Solar to hydrogen efficiencies of about 5% have been obtained. This is expectedly to rise to about 10% in 2010. If developments proceed as expected, PEC may become a better option than PV in producing hydrogen at reasonable cost in the moderate regions; e.g., in residential areas. This concept may even become of particular use in decentralized hydrogen production, e.g., to home-fuelers.

Appendix 2: Hydrogen from renewables

Experiences with hydro power electricity to hydrogen conversions have recently been evaluated (IEA Hydrogen production and storage, 2006). Current cost of hydrogen from hydropower electricity is shown in Figure II It can be seen that electricity is the major cost component in the aggregated electricity cost. In addition, it appears that all cost components are still sensitive to improvements.

The hydrogen from today's **small** electrolyser plants costs 4.4 US$ per kg. Using **large** plants the cost of hydrogen reduces to 3.3 US$ per kg. The reason is the higher efficiency of these systems.

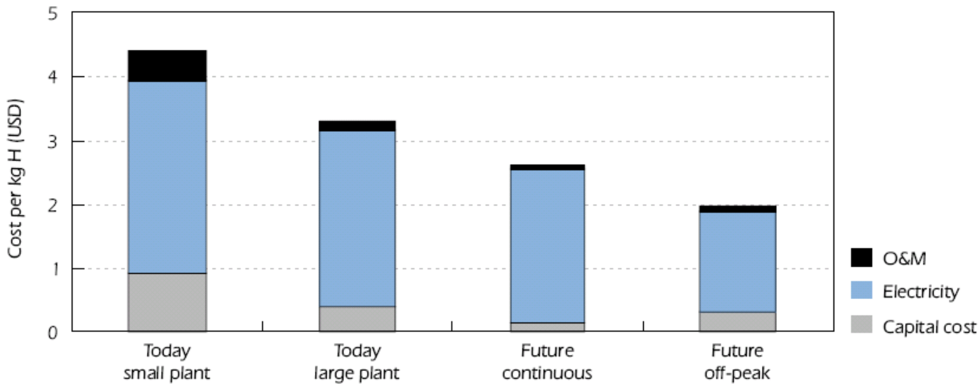


Figure II: Hydrogen production cost using hydro electricity (IEA Hydrogen production and storage, 2006)

To learn about the technical-economical perspectives, Nitsch and Fischedick 2002 have made a comparative study evaluating the cost of renewable hydrogen from different electricity producing renewable sources. Figure III shows the cost components of hydropower, wind, solar thermal and solar photovoltaic. In the calculations 3.0 ct/kWe has been applied for hydropower electricity. Beside the cost of electricity, the cost of hydrogen is strongly influenced by the number of productive hours over the year.

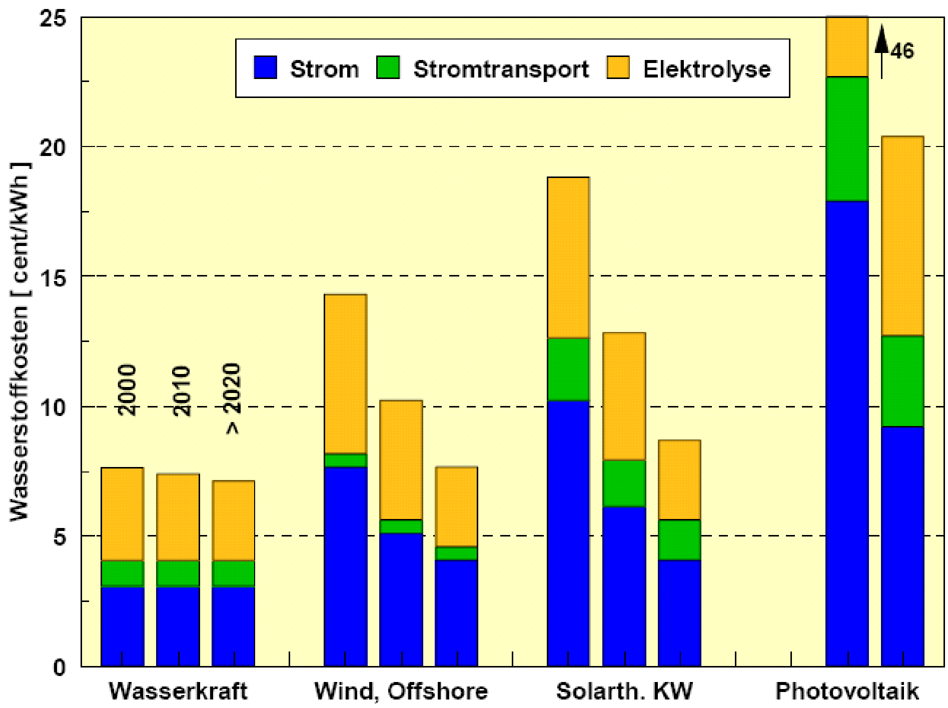


Figure III: Diagram by Nitsch, J and Fischedick.M (2002) comparing current and near future hydrogen production costs from different renewables

1 kg H2 = 141,89 MJ (HHV) = 39,414 kWh (3600 kJ=1 kWh)

The cost of the electrolyser is subject to improvements.
Beside improvements of the existing concept, developments are underway on the basis of the Polymer Electrolyte Fuel Cell (PEMFC).
This fuel cell type is favorite to be applied in the future fuel cell engine. This type seems to have the potential to become the key, low-cost component in fuel cell driven transport with hydrogen as the fuel, and will then be mass produced. The PEM electrolysers have potentially lower cost than the alkaline electrolyser would be very effective in cost reduction of the electrolysis

The PEMFC seems to make good progress to become the key, low-cost component in fuel cell driven transport with hydrogen as the fuel. For electrolyser use, a potential lower cost than the AFC based electrolyser would be very interesting; but the degree of success is uncertain.

These developments, which are expected to increase the efficiency and reduce the investment costs of the electrolysis process, will consequently decrease the cost of the solar hydrogen produced.

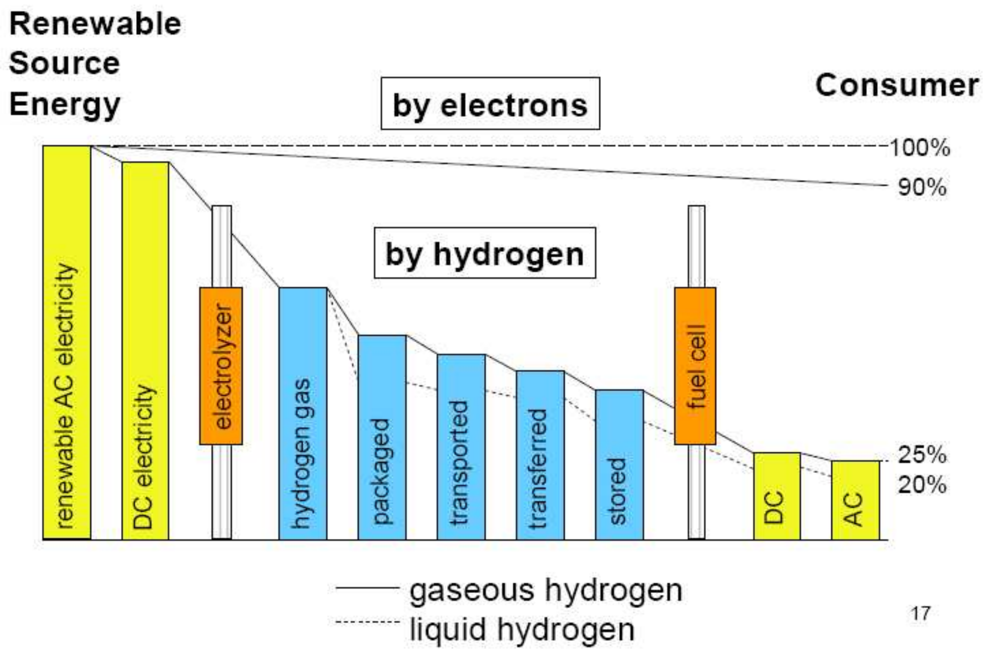


Figure IV: Comparing efficiency steps in long distance transport of renewable energy by electricity and hydrogen. (Source: Bossel, 2005)

Bossel: "Only 25 / 20 % of the original energy becomes useful for the hydrogen path" on arrival in Europe. He used the energy loss percentages given in the table below.

Table I

Hydrogen by electrolysis		25%
Compression	to 200 bar	8%
	to 800 bar	13%
Liquefaction	in small plants	50%
	in large plants	30%
Chemical hydrides		60%
200 km road delivery (Diesel)		
	at 200 bar	13%
	as liquid	3%
2000 km pipeline		20%
Onsite generation (electrolysis)		50%
Transfer from 100 bar to 700 bar tank		8%
Re-conversion to electricity by fuel cells		50%

Text box: Concentrating Solar Power Systems (see figure 3.1)

Text from source: www.solarPCES.org

Parabolic Dish Systems:

Parabolic dish systems consist of a parabolic-shaped point focus concentrator in the form of a dish that reflects solar radiation onto a receiver mounted at the focal point. These concentrators are mounted on a structure with a two-axis tracking system to follow the sun. The collected heat is typically utilized directly by a heat engine mounted on the receiver moving with the dish structure. Stirling and Brayton cycle engines are currently favored for power conversion. Projects of modular systems have been realized with total capacities up to 5 MWe. The modules have maximum sizes of 50 kWe and have achieved peak efficiencies up to 30% net.

Power Tower Systems:

A power tower converts sunshine into clean electricity for the world's electricity grids. The technology utilizes many large, sun-tracking mirrors (heliostats) to focus sunlight on a receiver at the top of a tower. A heat transfer fluid heated in the receiver is used to generate steam, which, in turn, is used in a conventional turbine-generator to produce electricity.

Early power towers (such as the Solar One plant) utilized steam as the heat transfer fluid; current US designs (including Solar Two, pictured) utilize molten nitrate salt because of its superior heat transfer and energy storage capabilities. Current European designs use air as heat transfer medium because of its high temperature and its good handability.

Individual commercial plants will be sized to produce anywhere from 50 to 200 MW of electricity.

Parabolic Trough Systems:

The sun's energy is concentrating by parabolically curved, trough-shaped reflectors onto a receiver pipe running along the inside of the curved surface. This energy heats oil flowing through the pipe, and the heat energy is then used to generate electricity in a conventional steam generator.

A collector field comprises many troughs in parallel rows aligned on a north-south axis. This configuration enables the single-axis troughs to track the sun from east to west during the day to ensure that the sun is continuously focused on the receiver pipes. Individual trough systems currently can generate about 80 megawatts of electricity.

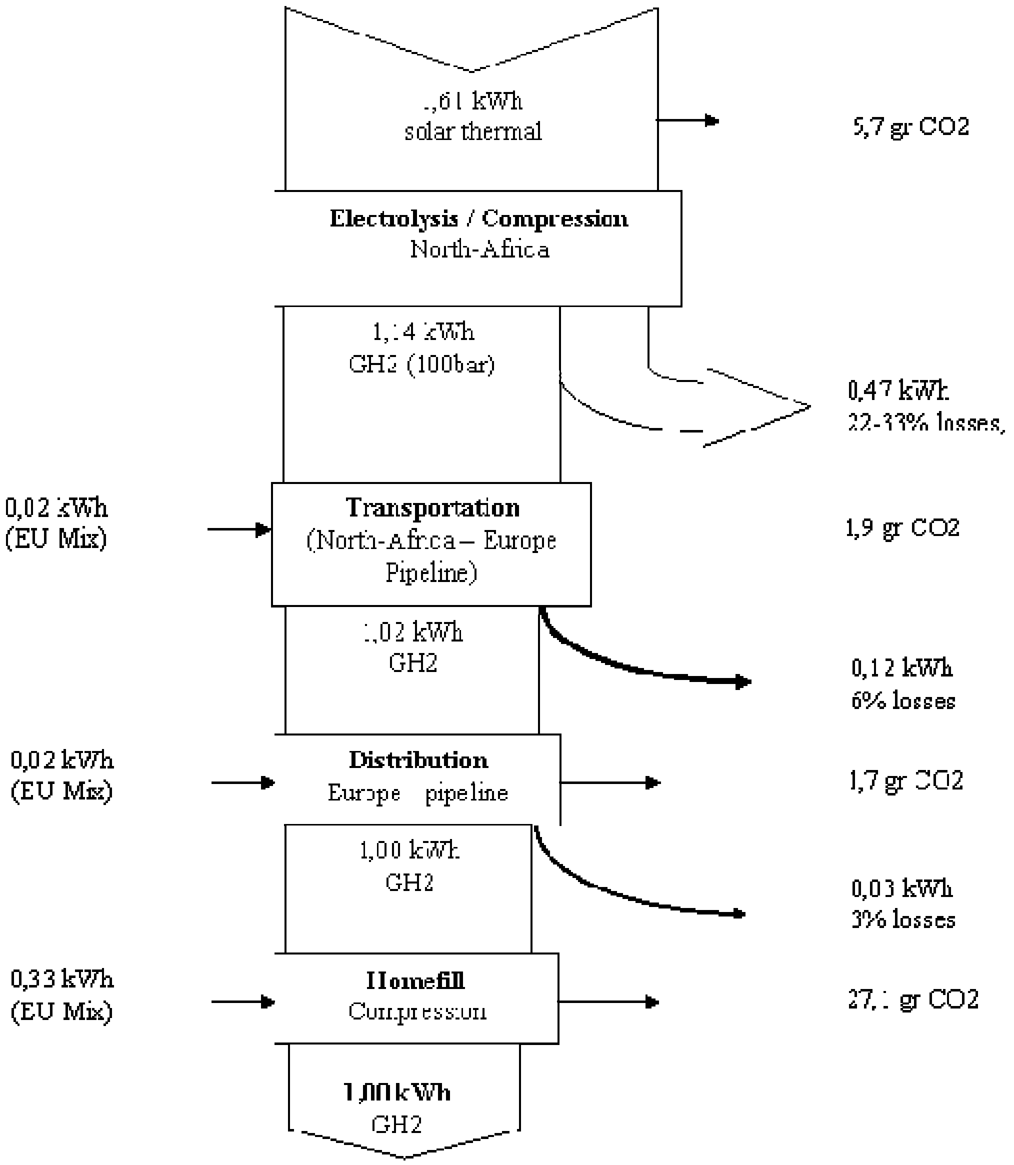
Trough designs can incorporate thermal storage—setting aside the heat transfer fluid in its hot phase—allowing for electricity generation several hours into the evening. Currently, all parabolic trough plants are "hybrids," meaning they use fossil fuel to supplement the solar output during periods of low solar radiation. Typically a natural gas-fired heat or a gas steam boiler/reheater is used; troughs also can be integrated with existing coal-fired plants.

Another option under investigation is the approximation of the parabolic troughs by segmented mirrors according to the principle of Fresnel.

Appendix 3: Sankey diagrams Fuel Chains

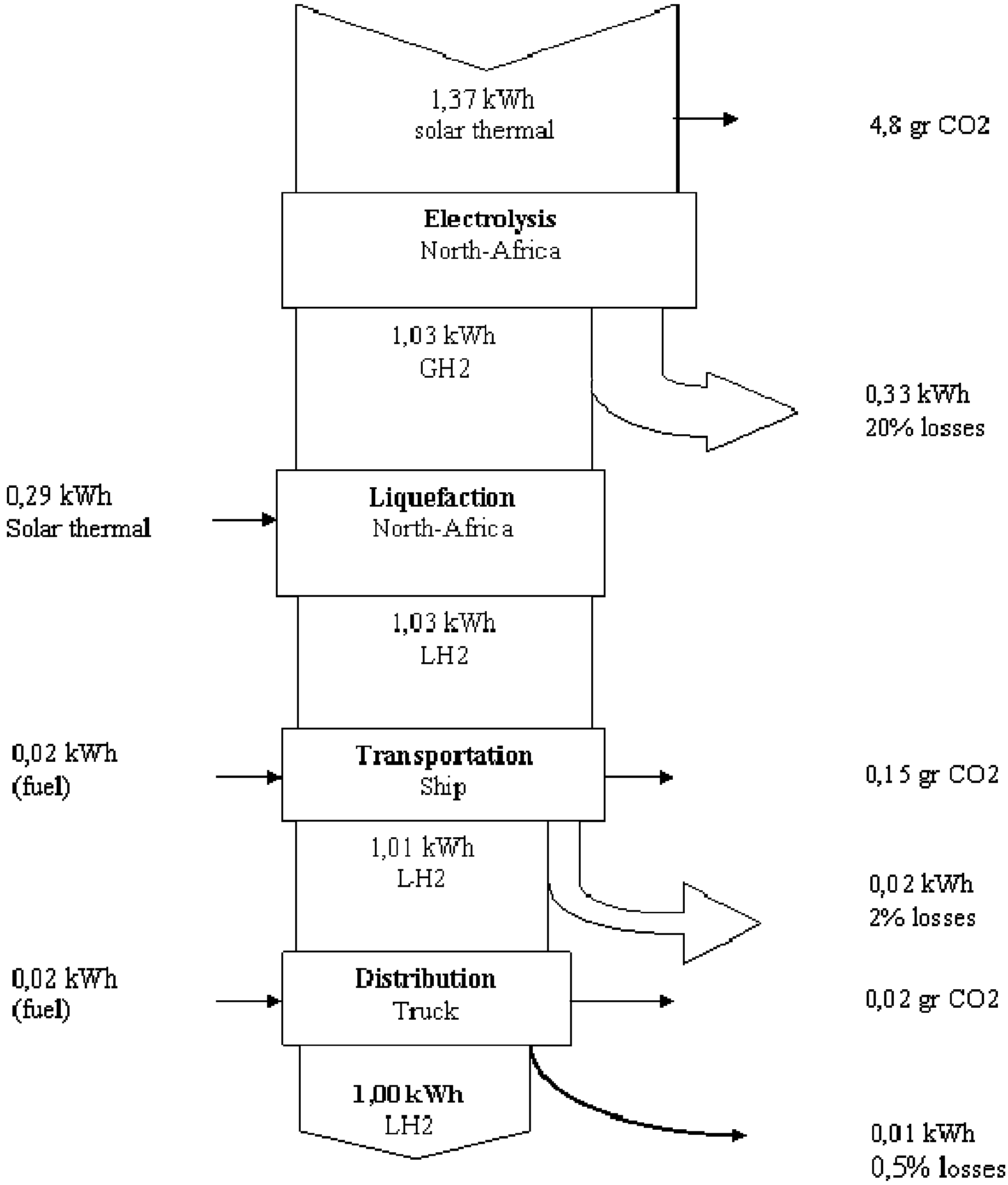
Sankey diagrams provide an overview of the primary energy used in (i) CSP electricity generation and (ii) individual chain steps (leading to GHG emissions).

1 GH2 route – pipeline – homefill - 2030



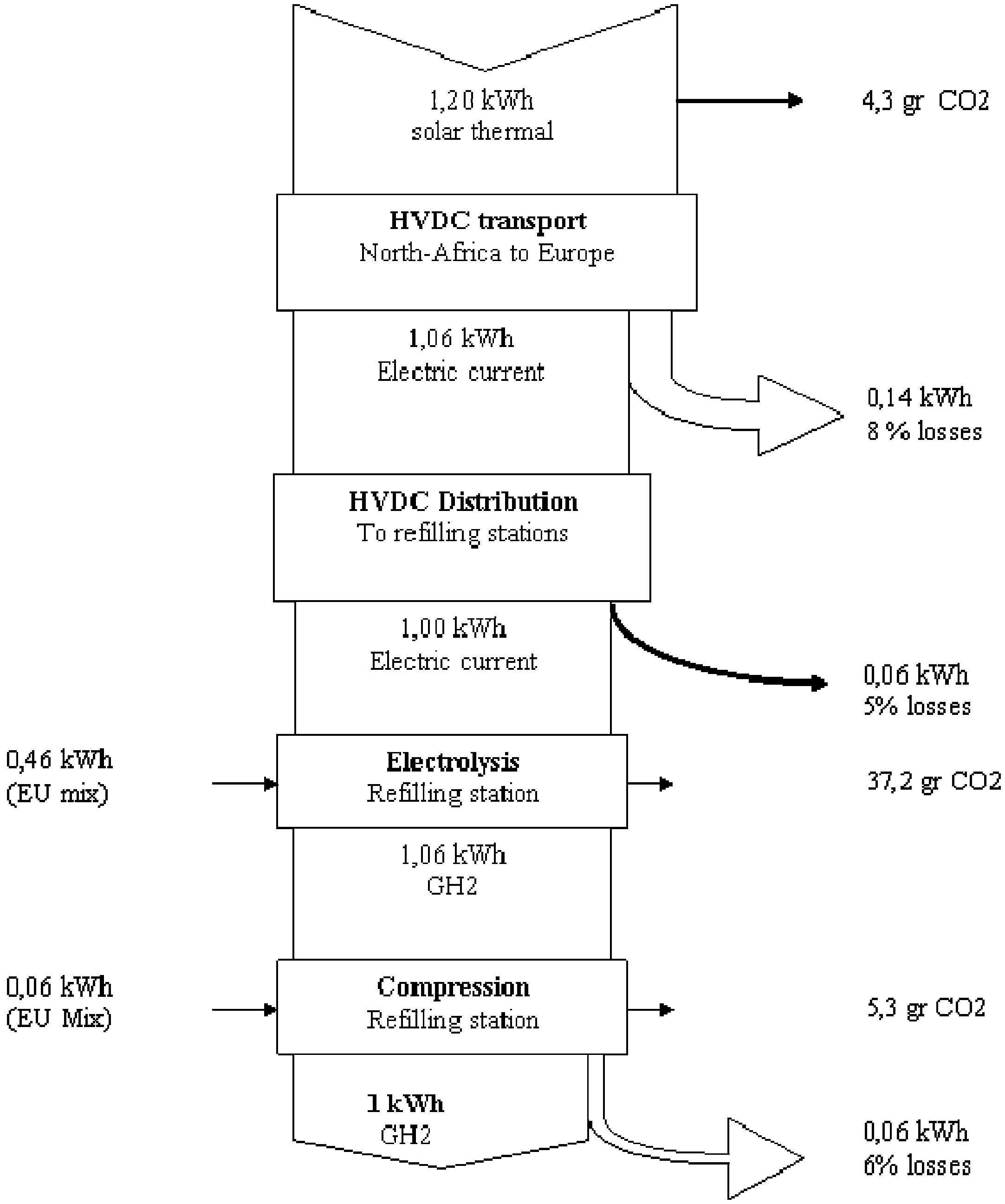
Primary Energy Demand:	1,98 kWh/kWh H2
GHG Emission:	36,4 gr/kWh H2

2 LH2 route – shipping – refilling station 2030



Primay Energy Demand:	1,67 kWh/kWh H2
GHG Emission:	4,9 g/kWh H2

3 HVDC electricity - Refilling station - 2030



Primay Energy Demand:	1,72kWh/kWh H2
GHG Emission:	46,7 g/kWh H2

Appendix 4 Overview CSP-installations

An overview of realized CSP installations or installations in progress is given in the following, based on Greenpeace[49] and Gezen[50].

Realized CSP installations

- Californië. Nine installations with a capacity of 354 MW, built in the period 1984-1990. Operator: Florida Power & Light Energy
- Tucson, Arizona. 1 MW installation; operational in 2006.
- Liddel, Australia. First phase operational in 2005

Commercial CSP installations currently built:

- Sevilla (Spain), 13 MW, operator: Solucar
- Boulder City, Nevada, USA; 64 MW, operator: Southern California Edison.

CSP projects in preparation

- Two 50 MW installations in Guadix, Andalusia (Spain) (Andasol project). Operators: Solarmillennium (Germany) and ACS-Cobra (Spain).
- 5 MW CSP-desalination installation in Aqaba, Jordan. Operator: Kernenergien, Stuttgart, Germany.
- Hybrid CSP installation, 220 MW (30MW solar), Ain Beni Mathar, Morocco. Operator: ONE (Morocco)
- Sixteen hybrid CSP installations, 150 MW (44MW solar), Algeria. Operator: NEAL (Algeria)

[49] http://www.greenpeace.org/raw/content/international/press/reports/Concentrated-Solar-Thermal-Power.pdf
[50] http://www.gezen.nl/archief/TransitiepadCSP-Aanmelding-1.pdf