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ENERGY PRODUCTION FROM SOLAR POWER SATELLITES
– THE HYDROGEN OPTION –

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ABSTRACT/RESUME

It is the purpose of this paper to give an overview on the concept of a hydrogen economy, in which hydrogen (H_2) is envisaged as energy carrier for power, heat and transportation purposes. The motivations for a transition to a hydrogen economy are discussed.

Furthermore, the potential role of solar power satellites (SPS) for the production of renewable hydrogen is presented. SPS-to-H_2 systems are discussed alongside with other hydrogen production vectors regarding the parameters cost, efficiency and specific CO_2 emissions.

From the discussions therein, it can be concluded that hydrogen and fuel cells are promising technologies which offer economical opportunities, customer benefits and which are environmentally sound provided that they are based on renewable hydrogen in the mid to long-term future. Solar power satellite systems could generate renewable hydrogen at potentially high capacity factors ('firm power') provided that cost and performance targets are met. In terms of production costs, SPS systems could then be competitive. However, the major hurdle to economic viability is space transportation. Regarding the specific energy effort to generate hydrogen for transportation purposes including grey energies, SPS could be in the lower range of other renewable and fossil primary energies. Here, results are sensitive towards the system architecture as well as space transportation. Life-cycle emissions attributed to SPS-to-H_2 systems could not be derived. The certainty of the result would be low as details in the system design remain subject to further in-depth investigations.

Not discussed are general important issues such as economic, political and environmental risks which certainly influence further development of SPS.

1. INTRODUCTION

”I believe that water will one day be employed as a fuel, that hydrogen and oxygen, which compose it, used alone or together, will furnish an inexhaustible source of heat and light and with an intensity that coal cannot provide. [...] Water is the coal of the future.”

Jules Verne "The Mysterious Island" (1875)

Jules Verne is the voice of the 19th century, the century in which the face of the industrial age was mostly covered by a black layer. He did not foresee the mushrooming oil and gas rigs that powered the 20th century, the century of fossil oil. Yet, he did foresee the hydrogen age, which is likely to become the energy carrier of the 21st century that will incorporate successively rising shares of renewable energies in the future energy mix. In retrospective, one will find that humankind went off-track for awhile to develop an activity so far unprecedented in the history of humankind and which is somewhat similar to the frenetic glow of a supernova. Back on track with renewable energies we will then find ourselves back to where humankind lived more than 99% of its history, yet with capabilities far beyond – in the good and in the bad.

Hydrogen is no longer exclusively a brainchild of visionaries but more than ever an issue for economists, engineers and soon even for the common users, too. Reasons for this are given throughout this paper including some food for thought on what the hydrogen option means to the other grand visionaries of today – the space community and namely its promoters of energy from space concepts.

2. HYDROGEN AS AN ENERGY CARRIER

Hydrogen and fuel cell technology hold the potential to revolutionize the way we will use energy tomorrow. Though revolutionary in its implications, a transition to a hydrogen economy can proceed at an evolutionary pace. Intermediate steps may be the use of carbon based primary energies in the near to mid-term, especially natural gas with its inherently low carbon to hydrogen ratio. These are eventually replaced by renewable hydrogen production options in the mid to long-term. Another intermediate step may be hybrid vehicles in the transportation sector. A successively rising share of electrical parts in the vehicle allows all stakeholders to gain experience until the (hydrogen) internal combustion engine is eventually complemented or even completely replaced by fuel cells. This will take place as soon as fuel cells comply with stringent automotive cost and performance targets.

2.1 Major Drivers

In such a transition process as described in the introduction of this chapter, external factors – such as a mandatory reduction of corporate average fleet emissions (so-called CAFE standards) – foster or prevent a fast and broad-scale introduction of hydrogen and fuel cell technology. For example, the Californian pollution prevention programs in recent years have been a major motivation for the automotive industry to develop alternative propulsion systems. Thus, political measures to protect basic environmental goods, such as air and water quality management, promote the introduction of hydrogen in conjunction with environmentally benign primary energies, especially in the transport sector.

More recently, energy security came on top of the political agenda. For geo-political reasons, major industrialized countries want to grow independent from energy imports. More than any other economic activity, the transportation sector is practically totally dependent from a single energy carrier – fossil oil.

The topic of energy security is closely linked to fossil fuel constraints. First signs of a beginning scarcity of oil and gas resources become visible. Trade prices develop an unpredicted volatility because of this and additional geo-political reasons.

Concerning these major drivers of a hydrogen economy, the power and will resides mostly with political bodies. However, hydrogen and fuel technology offers a wide range of technology and product innovations. These may either provide a direct benefit to the user when compared to conventional solutions (e.g. battery versus fuel cell) and/or offer new market opportunities.

2.2 Fields of Application

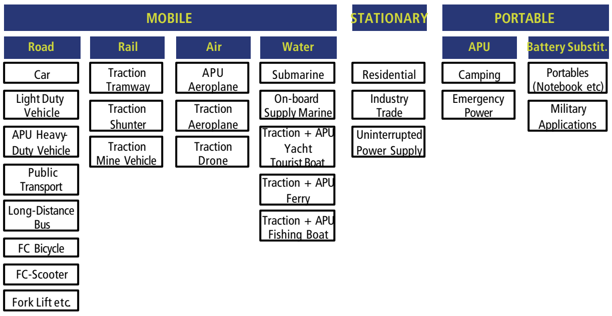
The fields of application of hydrogen and fuel cell technology are highly diverse. And there is no doubt that many more exist which are not yet even imagined. Hydrogen and fuel cell technology will have an impact on the **mobile** (vehicles, planes, ships), **stationary** (residential, commercial/ industry) and **portable** (emergency backup, notebook, cellular, PDA etc.) market.

Hydrogen propelled vehicles are currently the hydrogen applications which are most present in the public perception. By the end of this year, more than 100 hydrogen propelled vehicles will have hit the road almost exclusively in the framework of demonstration and validation trials.

Extensive research, development and demonstration (R,D&D) is undertaken in the stationary sector as well. Equivalent to the automotive business, virtually every major international company pursuits R,D&D in the field. The dominating motivations to develop hydrogen power plants for stationary purposes are decentralization and co-generation. Energy experts envision that decentralized operating fuel cells are then coupled together to form 'virtual power plants'. Large numbers of small (residential) and medium sized (district/ commerce / industry) CHP units may be operated as if it was one large-scale power plant. Thus, power is generated in the vicinity of consumption while process heat is not dumped in cooling towers.

Casio, Hitachi, NEC, Panasonic, Samsung, Sony, Toshiba, and many other newcomers are highly active in the field of integrating (mostly direct methanol) fuel cells into their range of products. Performance requirements of portable products such as notebooks, personal digital assistants and mobile phones are increasingly demanding. An ever increasing number of applications are integrated into a single product ('technology convergence'). Another design target is an extended operation time off-grid. Meanwhile, the development of these requirements proceeds faster than the improvement of existing and development of new, high-performance battery technologies. Hydrogen and fuel cells are the only portable energy source which may provide the possibility of off-grid 'recharge' on the fly. Furthermore, with portable devices 'recharging' is done within seconds by means of refilling.

Fig. 1 gives an overview over selected hydrogen/fuel cell applications.



MOBILE				STATIONARY	PORTABLE	
Road	Rail	Air	Water		APU	Battery Substit.
Car	Traction Tramway	APU Aeroplane	Submarine	Residential	Camping	Portables (Notebook etc)
Light Duty Vehicle	Traction Shunter	Traction Aeroplane	On-board Supply Marine	Industry Trade	Emergency Power	Military Applications
APU Heavy-Duty Vehicle	Traction Mine Vehicle	Traction Drone	Traction + APU Yacht Tourist Boat	Uninterrupted Power Supply		
Public Transport			Traction + APU Ferry			
Long-Distance Bus			Traction + APU Fishing Boat			
FC Bicycle						
FC-Scooter						
Fork Lift etc						

Fig. 1. Overview of selected hydrogen and fuel cell applications

Estimations which sector will be the first to be ready-to-market frequently changed in history depending on current technological breakthroughs (such as fuel cells for automotive purposes) and drawbacks (such as small-scale reformers). Furthermore, innovations in one sector usually also promote development progresses in other sectors.

In contrary to as proposed in some roadmaps, a creeping introduction of hydrogen vehicles in small numbers over several decades is very unlikely. Either techno-economic hurdles are overcome – then the automotive market is penetrated rapidly (why should the customer not buy the car with the better performance?) – or hurdles are not overcome – then the new technology will not enter the market at all (why should the customer buy the car with the lower techno-economic performance?).

In the following chapters, focus is put on mobile applications as this field is largely untapped regarding the concept of sustainability.

2.3 Potential Hydrogen Market

In future, hydrogen may play a key role in providing combined heat and power for the residential and industrial sector as well as fuelling tomorrow's transportation needs. Today, energy requirement from the transport sector alone represents approximately ¼ of the overall primary energy demand in the European Union (see Fig. 2).

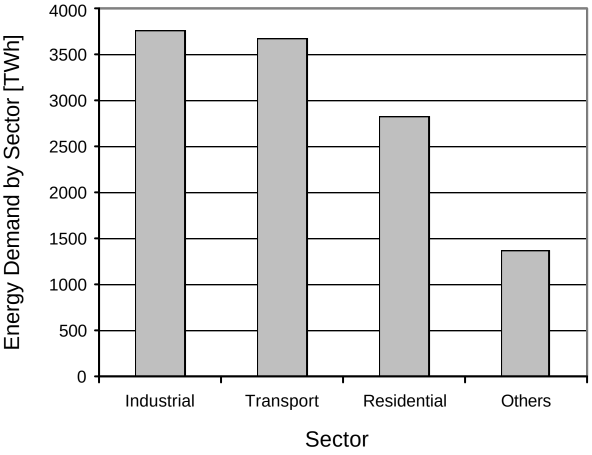


Fig. 2. Total final energy consumption (EU15, 2000) [1]

Whereas the energy demand from the industrial, residential as well as the 'others' sectors is drawn from a broad range of primary energies such as coal, nuclear, hydro power etc., today's primary energy base for transport purposes is almost completely confined to petroleum as indicated in Fig. 3.

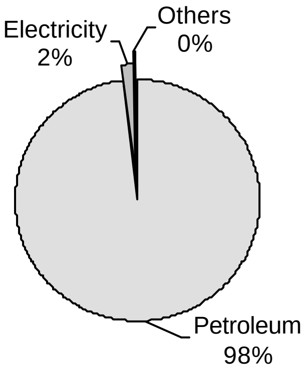


Fig. 3. Transportation energy split (EU15, 2000) [1]

Alternative transportation fuels may be based on fossil (gas-to-liquids and H_2), biomass (biomass-to-liquids and H_2) or any other renewable energy feed stocks (H_2). The potentials of biomass-to-liquids are limited in Europe. Fossil based gas-to-liquids do not provide a long-term perspective and require CO_2 capture and sequestration in order to be environmentally benign. It should be discussed whether the R,D&D effort for developing e.g. combined coal gasification and CO_2 capture and sequestration technologies are strategically the optimal solution or whether the financial effort and human power ought not be directed towards long-term solutions directly. However, the market for hydrogen energy for transportation purposes is potentially huge. In the future, transportation is especially prone to changes considering its dependency on fossil fuels.

2.4 Commitments from Industry and Politics

”Our objective is to realise a step-by-step shift towards a fully integrated hydrogen economy based on renewable energy sources by the middle of the century”

European Commission president Romano Prodi at the launch of the European Hydrogen and Fuel Cell Technology Platform in January 2004

2.4.1 Hydrogen/Fuel Cell Vehicle Announcements

According to industry announcements General Motors / Opel targets to have 50,000 – 100,000 fuel cell vehicles on the road by the year 2010. Ford published to target some 50,000 fuel cell vehicles within the same timeframe.

Japanese targets in the framework of the NEDO (New Energy and Industrial Technology Development Organisation) initiative [2] are:

2005 – 2010: 50,000 fuel cell vehicles; 2,100 MW_e stationary fuel cells

2010 – 2020: 5 million fuel cell vehicles; 10,000 MW_e stationary fuel cells

2030: 15 million (20%) fuel cell vehicles; 8,500 H_2 refuelling stations across Japan

2.4.2 Major Hydrogen/Fuel Cell Initiatives

Both the International Partnership on Hydrogen Energy (IPHE) [3] and the UNEP/GEF Fuel Cell Bus Project [4] are major hydrogen/fuel cell initiatives on an **international** level.

In **Europe**, the High Level Group for Hydrogen and Fuel Cell (HLG) was set in 2002 by the European Commission to bring together top-level stakeholders from across Europe with the aim of formulating an integrated EU vision on the possible role that hydrogen and fuel cells may play in the framework of a sustainable energy system. Based on their recommendations, the European Hydrogen and Fuel Cell Technology Platform (HFP) [5] started operation in 2004. It represents a platform for public and private stakeholders to promote the transition of the EU to a hydrogen economy. As part of the European Unions growth initiative, the projects ‚Hypogen‘ und ‚Hycom‘ will receive a cumulated funding of EUR 2.8 billion up to 2015. ‚Hypogen‘ will comprise a large-scale test facility for power and hydrogen production. ‚Hycom‘ shall foster the establishment of so-called ‚hydrogen communities‘ in the European Union. Some EUR 18.5 million are allocated in the 5th EU framework programme for the Clean Urban Transportation Energy (CUTE) [6] demonstration project in which 30 fuel cell buses as well as hydrogen production and refueling facilities are installed in nine European cities. Hydrogen economies are implemented on two islands: Iceland [7] and Utsira (Norway) [8].

A bilateral **US-EU** collaboration on the development of the hydrogen economy was launched in 2003. The collaboration aims at advancing hydrogen research and technology development and the establishment of harmonized codes, standards, and regulations. It shall support the work of the international IPHE initiative.

In 2003, president Bush announced the **US** ‚FreedomCar' (Cooperative Automotive Research) and ‚Hydrogen Fuel Initiative' [9]. All in all some US$ 1.7 billion are allocated over five years. Several regions have also announced to establish so-called ‚Hydrogen Highways'. Among other, these are California [10], Illinois as well as British Columbia (**Canada**).

NEDO is a parastatal **Japan**ese organization founded 1980 in the aftermath of the second oil crisis. Today, under the auspices of the Ministry of Economy, Trade and Industry (METI), NEDO is the main body for funding hydrogen and fuel cell R&D with an overall budget of ¥ 19.3 billion (~142 million EUR) in 2004 [11]. From 1993 to 2002 – in the framework of an 28-year R&D plan for hydrogen and fuel cells – the WE-NET project [12] was carried out providing basic research activities in the field of hydrogen and fuel cell technology. Its successor – the Japan Fuel Cell & Hydrogen Demonstration Project (JHFC) [13] – was established in 2003 to pursuit demonstration projects. Plannings for another public-private-partnership are underway. In spring 2005 a new company "FC R&D Center" (working title) shall be established which consists of METI and some 10 industrial partners, such as Toyota, Matsushita, Sanyo and Tokyo Gas. METI plans to assign ¥ 10 billion for five years. Companies are expected to invest from several hundred millions yens to one billion yen each [14].

All in all, signals from industry and politics are on 'go' for the hydrogen economy. Commitments as well as technological progress indicate that it's no longer a question whether the hydrogen economy will become reality but rather when it will enter the stage.

3. CONCEPT OF HYDROGEN ECONOMY

3.1 Primary Resource Basis

Hydrogen is a secondary energy carrier. The characteristic of a secondary energy carrier is that other forms of (primary) energy is required to produce it[1]. Primary energy sources for the direct use of electricity as well as for hydrogen generation are e.g. oil, natural gas, hydro, wind or solar energy. Further sources are byproduct hydrogen from the chemical industry, thermo-catalytic decomposition of water and (photo-) biological production e.g. from bacteria and algae.

There is a broad consensus from politics as well as automotive and even a significant share of energy companies that renewable energy is the only viable primary energy source for hydrogen in the long run. With renewable hydrogen, the environmental benefit compared to conventional energies is unrivalled. Europe alone provides a substantial and diverse resource base of renewable primary energies as shown in Tab. 1.

Tab. 1. Renewable energy potentials in Europe

Source	Potential TWh_e/yr	Remarks
Biomass	600	Europe w/o form. USSR [15]
Geothermal	2,030	EU30 [16]
Hydro	584	470 inland EU15 [17] 114 offshore UK [18]
PV	8,976	891 roof and facade EU30 (derived from [19]) 3,356 former agricult. land EU30 (derived from [19]) 4,729 other (arid etc) land EU30 (derived from [20])
SOT	4,644	EU30 (derived from [20])
Wind	4,000	1,000 onshore 3,000 offshore

In order to get an idea about the meaning of the potential figures in Tab. 1: in 2000 the total electricity demand of EU15 was some 2,570 GWh_e.

However, the potentials stated in Tab. 1 may not be summed up straight forward as they may compete with each other to a certain extend, e.g. regarding land usage.

The calculation of energy production potentials is highly sensitive regarding the underlying assumptions. Depending on the set of assumptions chosen, renewable energies potential in the EU alone might not be able to cover the overall electricity and transportation energy demand if energy savings are not taken into account. In such a case, the EU would have to import renewable energy from e.g. North African solar power plants as discussed in Ref. [21] and [22] or further rely on non-renewable energy sources such as coal.

Furthermore, especially wind and solar energy are fluctuating by nature. Variation in energy supply may be eased by combining wind and solar energies in an appropriate way, advances in weather forecasts and installing energy storage facilities, such as pumped hydro as far as geographically available and hydrogen for transportation or combined heat and power (CHP) purposes. Though biomass, geothermal, hydro power and demand side energy management may also be applied for balancing energy production and demand, space-based solar power systems may provide an additional source of firm power to the electricity grid. If published technical and cost targets are met, SPS could be a valuable addition to the future renewable energy supply portfolio from a grid operator's point of view.

Frequently, discussions arise even among promoters of renewable energies whether the relatively small shares of renewable energies in the beginning of the transition phase towards a sustainable energy system shall be used primarily directly for grid-connected electrical

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[1] From a scientific point of view energy cannot be 'produced' but only changed from one state to another. Throughout the paper this common phrase is applied nonetheless.

appliances or for transportation purposes. This is a somewhat artificial and ideological discussion. The market will tell which demand is willing to pay which price in order to have either stationary or mobile wants supplied by renewable energies. In fact, it's no question of 'either/or' but rather a question of 'as well as'. Ultimately, both stationary and transportation will have to be transformed to comply with the 4+ basic sustainability rules [23].

3.2 Hydrogen production pathways

The hydrogen economy may comprise a broad range of technical solutions for hydrogen production, storage, transport and usage (see Fig. 4). There is no single optimum solution. Technology assessments and forecasts are thus a complex issue which highly depend on the very frame conditions. Though difficult for predictions of any kind, the technological flexibility offered by hydrogen as a secondary energy carrier is its major strength. E.g., the hydrogen economy is fueled by a broad base of energies. Various technology vectors for downstream treatment and application may co-exist. The optimum vector is subject to the very local conditions, i.e. the prevailing primary energy sources and energy consumption patterns. In Fig. 4 the hydrogen production and distribution pathways are shown for mobile applications only. Similar system architectures exist for portable and stationary applications.

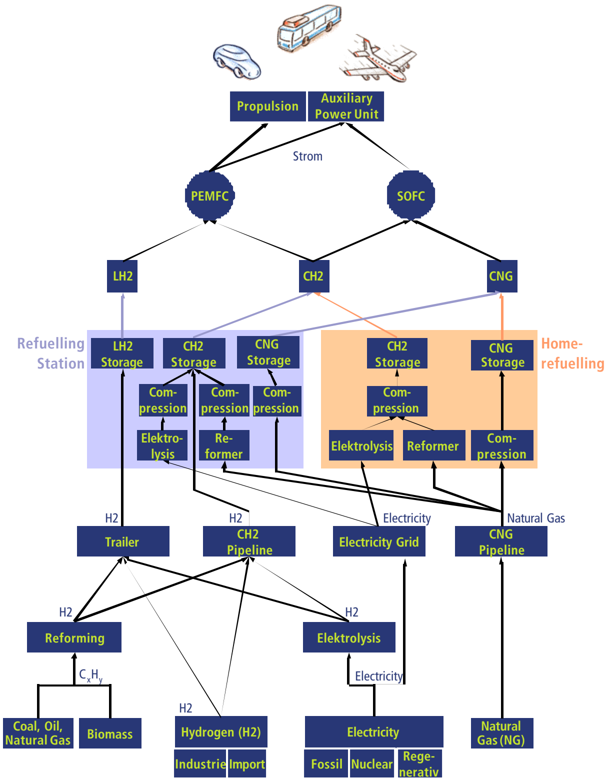

Fig. 4. Principle technology pathways for the supply of hydrogen for transportation purposes

In the hydrogen economy, two principle structural differences exist which may likely co-exist in future: It is the concept of centralized versus decentralized hydrogen production. Today, the provision of fuel is solely covered by centralized processing plants. With increasing penetration of renewable energies this picture is likely to become successively diversified. Renewable energies are by nature dispersed energies, i.e. the power density in terms of extracted usable energy per area is low compared to fossil fuels. Exemptions may be space-based solar power systems and large-scale solar thermal as well as offshore wind power plants.

One of the major benefits of hydrogen as an energy carrier is the flexibility and interoperability regarding its means of generation and consumption. Substantial synergy effects result thereby.

For the purpose of this paper, a simplified hydrogen supply vector for automotive purposes is defined as depicted in Fig. 5. Using a conservative approach, no synergies between hydrogen powered stationary and mobile applications are assumed.

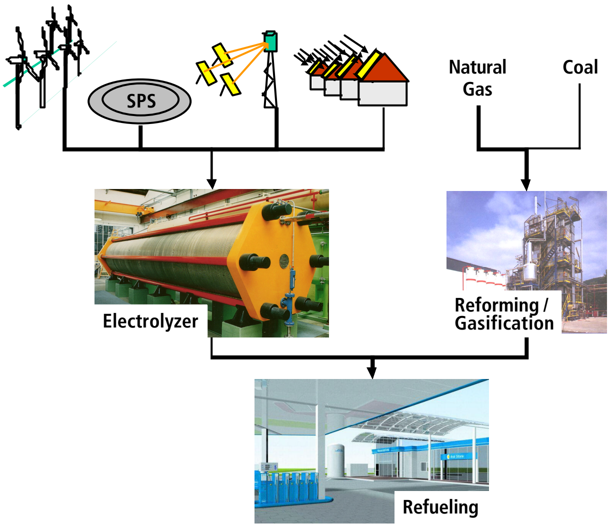

Fig. 5. Selected hydrogen production and supply vectors

It is assumed that hydrogen is generated from various primary energy sources either via electrolyzer (off-shore wind, SPS, PV and solar thermal power plants) or via reforming / gasification (NG, coal). Hydrogen generation, compression and storage occurs onsite at the refueling station with the exception of coal. Tab. 2 comprises the major technical assumptions for this hydrogen supply vector.

Tab. 2. Basic parameter assumptions (2030)

Source	**Description**
SPS	7,884 h/yr, Solar Disc [25] [27]
Wind	3,000 h/yr, offshore
PV	1,300 h/yr, mono-Si, solar-grade-Si, European sunbelt, cumulated installed: 150 GW_e ex-inverter, 0.22 €/kWh_e, 2,400 €/kW_{e_modul}, performance ratio: 0.75
SOT	6,400 h/yr, European sunbelt, >10 GW_e installed, 0.035 €/kWh_e, 2,300 €/kW_e
NG	steam reforming, onsite, 0.065 €/kWh_{NG} (LHV), without CO_2 capture + sequestration
Coal	gasification, 550 MW coal throughput per unit (1,600 t/d), 46 €/t_{coal}, 3,750 €/(Nm^3/h), without CO_2 capture + sequestration

Fueling Station	Electrolyzer 1,500 €/(Nm³/h), 4 double-dispenser units per station, cumulated >10,000 stations in EU-15

Regarding the cost of natural gas a tripling of current prices is assumed for 2030 due to an overall rising demand in conjunction with increasing resource constraints [24].

3.3 Results

In the following subchapters, the results derived from the hydrogen production vectors defined in Fig. 5 are presented. Analogue to Ref. [25] the time horizon for the underlying assumptions and calculations is 2030. Calculations were performed by means of the LBST proprietary software E3-Database (Energy, Emissions and Economy) [26]. The database comprises extensive information gained from a number of key projects which were mostly conducted in close co-operation with partners from the energy and automotive sector.

3.3.1 SPS Supply Potential

Except during the eclipse seasons, SPS is primarily attributed to provide power at a capacity factor of nearly 100%. Assuming an average sized car propelled by hydrogen (4 l_{oe}/100km) and an average annual mileage (12,000km), the following numbers of vehicles may be supplied from different SPS scenario sizes (see Tab. 3).

Tab. 3. Hydrogen supply potential of SPS in numbers of average sized and utilized cars

Scenario **[GW_e]**	0.5	5	10	50	100	150	500
CGH_2 **[million cars]**	0.52	5.2	10	52	105	157	523
LH_2 **[million cars]**	0.46	4.6	9	46	91	137	456

From Tab. 3 a **SPS rule-of-thumb** can be concluded according to which **for each GW_e of installed supply capacity, some one million cars could be powered**.

3.3.2 Energy Effort

The specific energy effort is calculated in a life-cycle assessment (LCA). Including grey energies (i.e. primary energy required to produce basic construction material), the following results are obtained as depicted in Fig. 6.

It can be seen that the energy effort for producing 1 kWh of compressed gas hydrogen is in the lower range of alternative primary energies. Two different sets of assumptions for space transportation were taken into account: the NASA assumptions [27] and the Neptune space vehicle concept by Koelle [28], [29]. The latter proposes a reusable 6,000t three stage heavy lift earth launch vehicle with a nominal payload of 350t (earth to LEO). The concept comprises a combined propulsive force equivalent to some 50 space shuttle main engines.

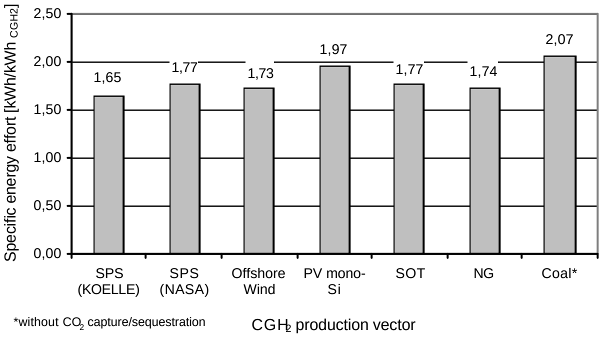

Fig. 6. Energy effort for CGH2 production and supply

The key figure 'energy effort' is of special importance when assessing non-renewable energy systems. There, system boundaries may be affected due to resource constraints and/or environmental pollution. With renewable and reusable energy systems, the conversion efficiency of power generation processes is actually of no relevance apart from the economic effort which is reflected in the generation costs (see 3.3.4).

The energy effort for natural gas and coal processes are best guess assumptions as no CO_2 capture and sequestration was assumed. However, the results thus gain in reliability. Published concepts indicate a great bandwidth for both energy and cost efforts for CO_2 conditioning.

3.3.3 Greenhouse Gas Emissions

Global climate change is attributed to human induced emissions of greenhouse gases (GHG). Among others, these are above all CO_2, CH_4 and N_2O.

Accomplished by General Motors (GM), 32 out of some 90 possible fuel pathways comprising various primary energy sources, secondary energy carriers as well as powertrain concepts for transportation purposes were assessed by LBST in a Well-to-Wheel analysis [26]. GM provided the Well-to-Tank analysis based on its current Opel Zafira platform. Furthermore, particular input and guidance on the Well-to-Tank analysis was provided by BP, ExxonMobil, Shell and TotalFinaElf. In general, four major fuel pathways were assessed: crude oil, natural gas, electricity and biomass based pathways. The assessment is complementary to a North American study conducted by GM and the Argonne National Laboratory [30].

From Ref. [26] it can be concluded that fuel cell vehicles offer the potential to greatly reduce overall GHG emissions if renewable energies are applied. Almost zero Well-to-Wheel GHG emissions are attributed with hydrogen powered fuel cell vehicles if the best renewable pathways are applied for hydrogen generation, such as wind. Long-distance transportation of hydrogen can spoil emission reductions. GHG emissions of biomass based transportation fuels is very sensitive towards production conditions, such as former land use, soil type, fertilizer and pesticides.

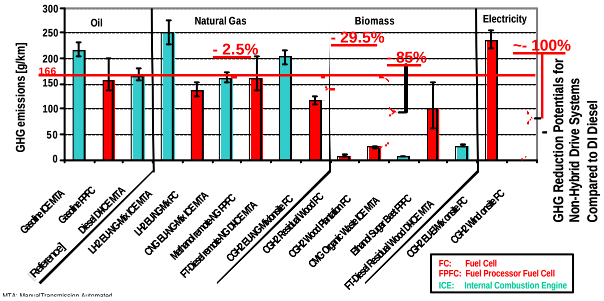

Fig. 7. Well-to-Wheel GHG emission reductions of selected fuel pathways compared to a Diesel ICE [26]

Taking a look at GHG emissions attributed with hydrogen production and sale at a fueling station, the following results apply for different primary energies as shown in Fig. 8.

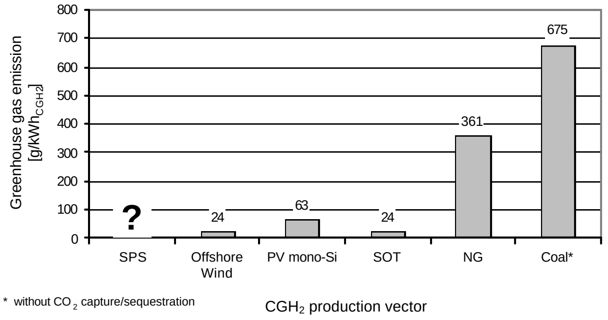

Fig. 8. Specific greenhouse gas emissions for the production and supply of CGH_2 from various sources

Though crucial for the overall sustainability of SPS-to-Hydrogen systems, a Well-to-Tank assessment could not be undertaken. This is mostly due to the current state of knowledge regarding details in SPS system design. Eventually low certainty of results does not allow for the application of first estimations. Here, further in-depth investigations are essential. Results from energy payback time calculations in Ref. [25] indicate that SPS systems are significantly sensitive regarding the space transportation concept applied.

For a general rule-of-thumb, it can be concluded from numerous LCA studies that hydrogen energy – be it for stationary, mobile or portable purposes – is as environmentally benign as its primary energy source.

3.3.4 Hydrogen Production Costs

In Fig. 9 the cost of hydrogen from various primary energy sources are stated ex refueling station.

Without space transportation the cost of compressed gas hydrogen ex refueling station is in the upper range of most of the alternative primary energy sources (see the first bar graph of Fig. 9). The only exception is PV-based hydrogen which is a factor of three more expensive than any other alternative primary energy (renewable as well as fossil energy) even when taking into account expected cost degressions by 2030.

Treating space transportation as an open parameter results in significantly higher hydrogen production costs from SPS which almost double at 1,000 EUR/kg$_{payload}$ transportation costs.

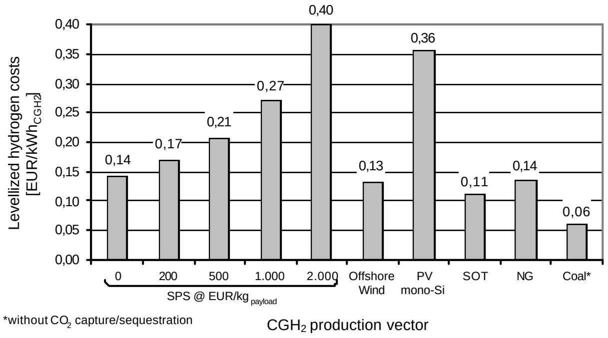

Fig. 9. Cost of CGH_2 from various energy sources

From an economical point of view hydrogen from SPS becomes increasingly less attractive with rising launch costs. The overall economic viability of hydrogen generated from space-based solar power systems is thus highly sensitive to the cost of space transportation.

This sensitivity is in accordance with results obtained from Ref. [25] for power production only. At specific space transportation costs of some 1,500 EUR per kg payload, the cost of the SPS-to-H2 vector is eventually higher than PV-to-hydrogen. Today's cost of space transportation is some 10,000 EUR/kg$_{payload}$.

It has to be noted that neither CO_2 capture nor sequestration was assumed for both natural gas and coal. Doing so would increase the related hydrogen production costs.

4. CONCLUSIONS

Major drivers for the introduction of renewable hydrogen are energy security, fossil resource constraints, environment and technology/product innovations.

Supply of hydrogen as transportation fuel is a potentially attractive target market for SPS.

Depending on the underlying assumptions, the renewable energy potential in Europe could be insufficient to meet both the European power and fuel demand.

SPS attributed energy effort for the production and supply of hydrogen for transportation is comparable to other renewable fuel supply options.

SPS attributed release of greenhouse gas emissions are subject for further research.

SPS production costs significantly depend on the cost of space transportation. A cost advantage of SPS over other hydrogen production options is not necessarily given.

5. ACKNOWLEDGEMENT

SPS data are based on the outcomes of a study commissioned by the ESA Advanced Concepts Team under ESTEC contract no. 17682/03/NL/EC (see [25]).

6. ACRONYMS AND ABBREVIATIONS

CHP	Combined Heat and Power
H_2	Hydrogen
l_{oe}	Liter Oil Equivalent
LBST	L-B-Systemtechnik GmbH
LEO	Low Earth Orbit
LHV	Lower Heating Value
R,D&D	Research, Development & Demonstration
SOT	Solar Thermal power plant
SPS	Solar Power Satellite

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