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Market potential analysis for the Introduction of hydrogen energy technology in stand-alone power systems

H-SAPS

INTRODUCTION

A large number of stand alone power systems (SAPS) is installed around Europe. These systems provide power to technical installations and communities in areas that are not connected to the regional or national power grid. An increasing number of SAPS include renewable energy technologies (RETs), i.e. solar or wind power, most often in combination with diesel generators and/or batteries for backup power, but the majority of larger SAPS are still based on fossil fuel power generation. Replacing diesel generators and batteries in SAPS by fuel cells running on locally produced hydrogen would diminish fossil fuel dependence, improve environmental standards, and possibly reduce operation and maintenance costs. The fuel cell technology is developing fast and the SAPS market is believed to be a market segment where hydrogen energy technologies can be competitive in the medium term.

A two-year Altener study with the acronym H-SAPS (Hydrogen – Stand-Alone Power Systems) was undertaken by two research institutes; the Institute for Energy Technology (IFE – Norway, co-ordinator) and the Centre for Renewable Energy Sources (CRES – Greece) as well as two companies directly involved in planning, installation and operation of conventional SAPS; Trama Technoambiental (TTA – Spain) and Econnect (UK).

The aim of the study was to:

1. establish a broad understanding of the technical and economical market potential for H-SAPS that are based on local renewable energy sources.
2. identify and quantify the technological and practical issues relevant to the H-SAPS market and draw the attention of related industry towards solving problems related to component integration and the needs of the user market.
3. identify the legal, regulatory and administrative hurdles for the H-SAPS market development and draw the attention of authorities towards amending such problems.
4. propose a roadmap for demonstration projects for H-SAPS installations.

Technologically the project was limited to small and medium sized SAPS, up to a few hundred kW in power output. The project is also limited to renewable energy as the only source of energy. Uninterruptible power supply systems or other kinds of back-up power systems installed in areas where grid connection is available were not considered. Small hydropower or other RETs, which have readily available energy storage capacity (geothermal, biomass) were similarly not included.

The aim of this brochure is to disseminate our results on technical challenges and opportunities of hydrogen technology in SAPS. In addition, an analysis of the supply and demand side of the market for H-SAPS will be given. The outline of a SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis of H-SAPS as an energy system product is also found at on the back-side of this brochure. Finally, some general conclusions and policy recommendations will be presented. For a more details on the project the reader is referred to the project reports, which may be download at www.hsaps.ife.no.

MOTIVATION

There are today 2 Billion people –one third of the world's population– that do not have access to a reliable electricity supply. In Europe alone, approximately 300,000 residential units have no access to the grid. These are mainly located in remote areas such as islands or mountain regions. The market for H-SAPS, as defined in this project, will emerge from the renewable energy market. The favourable economy of renewable energy compared to diesel generation has already been proved for specific sites and an example of island and mainland diesel costs compared to wind generation is given in table 1 (example taken from the UK).

TABLE 1.
Electricity generation costs from diesel and small-scale wind power

Island diesel	0.34 € / kWh
Mainland diesel	0.074 € / kWh
Small scale wind power	0.060 € / kWh

The integration of renewable energy generation into SAPS presents technical challenges, some of which are listed below:

- ✔ Stability through frequency control
- ✔ Long term energy storage
- ✔ Low renewable energy penetration
- ✔ Load growth
- ✔ Fluctuating generation & load
- ✔ Security of supply
- ✔ Energy dumping

Most SAPS systems will be based on AC-mini-grids due to the low availability of DC-appliances. These power systems need to maintain their frequency within a very tight specified range around a nominal point, in order to ensure safe operation of the electrical equipment connected to the electricity supply. Mismatch between power generated and power consumed by loads affects the frequency of the system, specially of SAPS. In large systems, like national grids, the variations are more easily evened out because of the size and inertia of the system. On the generation side, renewable energy sources do not provide a con-

ALTENER is the European Union non-technological programme aimed at promoting the use of renewable energy sources within the Union. ALTENER has been designed to make a meaningful contribution to the achievement of the Community objective of a significant increase in renewables.

Programme Objectives

ALTENER II is managed by DG TREN, the European Commission's Directorate-General for Energy and Transport. Its main role is to help create an appropriate environment for the Community Strategy and Action Plan for renewable energy sources. The programme also encourages both private and public investment in the production and use of renewable energy.

ALTENER II's specific objectives can be summarised as follows:

- To implement and complement Community measures designed to develop the renewable energy resource potential.
- To encourage the harmonisation of products and equipment in the renewable energy market.
- To support the development of an infrastructure that will increase investor confidence, stimulate the take-up of renewable energy technologies and improve the sector's competitiveness.
- To improve information dissemination and co-ordination at the international, Community, national, regional and local level, thereby increasing investor confidence and market penetration.
- To increase operational capacity for the production of energy from renewable energy sources.
- To implement the Community's renewable energy strategy.

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SWOT ANALYSIS

To evaluate the introduction of hydrogen technologies in SAPS, a SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis was conducted. The analysis was based on information collected from questionnaires, experience of the technical staff of H-SAPS consortium and other sources (literature, personal contacts with hydrogen energy providers etc.).

Strengths and Weaknesses refer to the product itself (SAPS with hydrogen as an energy carrier in this case), while Opportunities and Threats refer to the external environment affecting market development of the product. The results of SWOT analysis are shown in following table.

Strengths	Weaknesses
1. No need for fuel transport infrastructure 2. Already existing experience in handling of compressed gases 3. Noise level of the main competing systems (e.g. Diesel Engine Generators Sets) 4. Potential for high density energy storage 5. Seasonal energy storage without energy loss over time 6. Able to handle power fluctuations and therefore ideal for integration with intermittent renewable energy sources 7. Guarantied power from a renewable energy sources system 8. Potential for low and predictable O&M costs 9. Reduced environmental impact compared to conventional energy sources 10. Safety of power and energy supply	1. Missing codes and standards (safety issues, technical specifications, etc.) 2. Technology immaturity of fuel cells and PEM electrolysers 3. Low availability and high cost of small electrolysers 4. Lack of after - sales support 5. Procurement cost 6. Lack of component and system life - time experience 7. Weak supply network (consultants, engineers, entrepreneurs, etc) 8. Few dedicated complete system deliverers
Opportunities	**Threats**
1. Already existing Stand - Alone Power Systems driven by Renewable Energy Sources in which hydrogen technologies can be incorporated 2. Current EU and national financing schemes 3. New job opportunities 4. Diversification of companies involved in the energy sector 5. Reduction of environmental impact	1. Potential end users have no experience 2. No public available market study for SAPS in EU 3. Inadequate commercialisation plan 4. Limited practical experience due to few true Stand-Alone Power Systems with hydrogen as an energy carrier (HSAPS) installed 5. Hydrogen as a storage medium for energy in SAPS is not known and accepted 6. Inadequate legislative framework (standards, regulations, permissions of installation) 7. Low interest and priority from utilities and major suppliers of SAPS components/systems

tinuous level of power. Wind and solar energy fluctuates rapidly, even within seconds, whilst hydro, biomass and geothermal energy output vary on a daily or seasonal basis. This leads to a system where it is difficult to provide stable electricity supply at all times. On the demand side, as more loads are added to the system, the power mismatch is aggravated, which leads to intermittent shut down of the system, with blackouts when too many loads are switched on and there is a lull in generation, and dumping of excess energy when the generation is too high and few loads are switched on.

There are several potential solutions to these challenges:

- ✔ Energy storage
- ✔ Spinning reserve
- ✔ Over capacity
- ✔ Load control

Energy storage:
- Hydrogen energy system
- Flywheel
- Pumped hydro
- Compressed air
- Electrochemical storage

Load control:
- Match load to generation
- Low priority loads
- Co-operation from community

Installation of excess capacity and enabling a spinning energy reserve would normally not apply to SAPS for economic reasons, but load control and energy storage are both viable solutions for SAPS. Hydrogen technology has the potential to offer a compact and environmentally benign way of storing energy with low Operation & Maintenance (O&M) cost. Hydrogen also offers the possibility to increase the renewable energy penetration to 100%.

MARKET IDENTIFICATION – THE DEMAND SIDE

The current and future market for H-SAPS, comprises high-end cost segments of customers already connected to an electricity grid, customers with a conventional SAPS solution and customers without electrification. Figure 2 shows the three market segments for H-SAPS.

The major effort to describe the market for H-SAPS was done by firstly contacting power companies and grid-owners in the project partner countries (UK, Greece, Spain, Norway). Secondly, energy authorities and major energy consultancy companies and institutes in all European countries were identified and contacted through a questionnaire.

Because the user, in most cases, is interested in the service and not in the technology, detection of the market for H-SAPS is difficult if the different applications are not taken into account. The following categories were identified:

- Rural residences - houses and villages
- Rural tourism
- Agricultural applications
- Water pumping and treatment
- Communications

In the following each of these applications will be described.

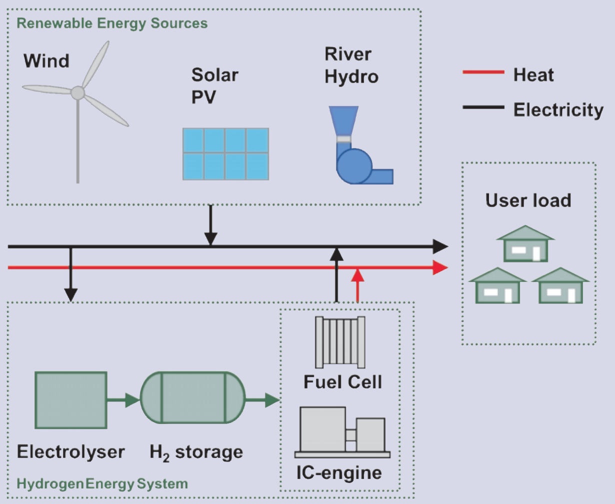

Figure 1. Schematic of an HSAPS system

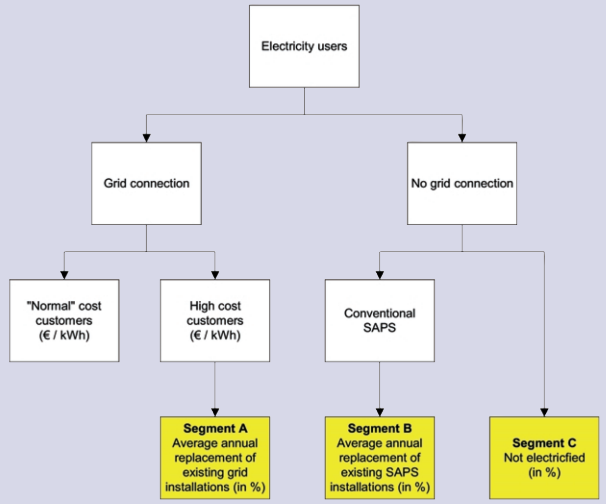

Figure 2. Categorisation of the electricity users. The market segments (A, B and C) for stand-alone power systems are shown in the yellow boxes.

Figure 3. Examples of rural residences with SAPS in northern Spain, from left to right: Cal Toniquet (Saldes, Barcelona), Town of San Felices (Agüero, Huesca) and town of Cal Peraire (St. Iscle de Vallalta, Barcelona) – *Photos courtesy of SEBA*

Rural residences - houses and villages

Rural electricity has to be supplied at the same quality as with the electrical grid except for the additional constrain of limited energy supply. This calls for a reliable system. Low-priority loads, however, may be disconnected in the case of expensive electricity supply (genset working, batteries empty).

The load profile of rural residences is characterised by seasonal and daily fluctuations depending on the usage of the residence. Typically, there are a lot of secondary residences included in this market segment with only seasonal or week-end occupation. There are rather few villages with clustered houses not connected to the grid in Europe. The power range encountered is between 600 W and 5 kW for rural households and up to 40 kW for rural European villages. Nevertheless, in a study carried out in Spain, typical daily load profiles could be filtered out for different types of users that gave an input to the estimations for the feasibility of H-SAPS.

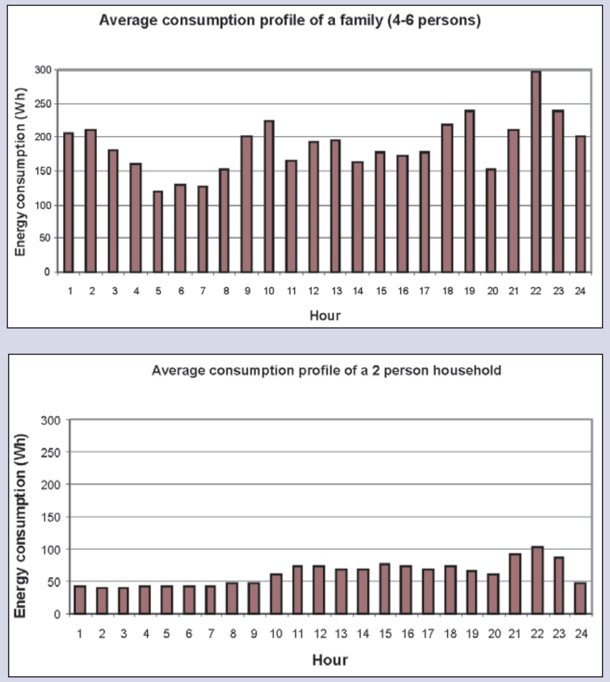

Figure 4: Typical load profiles encountered in SAPS installations managed by the users association SEBA in northern Spain.

Rural tourism

Rural tourism services are often located in remote areas, sometimes in natural parks. Thus they are often not grid connected and operate diesel engine generator sets (DEGS). The renewable part of a hybrid system helps to drastically reduce the operating hours of the DEGS usually operated, especially in the hours of partial load.

Rural tourism services are often owned by municipalities or associations, sometimes by individuals. Hbrid systems have to provide reliable electrical energy, as it is essential for the operation of the establishment.

Rural tourism is often characterised by a punctually strong electricity demand, caused by kitchen and restaurant services. The power range encountered is between 2 kW and 20 kW. This demand is strongly fluctuating (strong demands on weekends, low demand when kitchen is not operative). Other electricity demands, less strong, come from illumination, rural phones, television sets, etc. The load profile is similar to that of residences.

Agricultural applications

In this sector there is a wide spectrum of applications. Nevertheless only rather small farms are still without connection to the grid. High consumption peaks sometimes mark the load profile during working hours, but the overall energy consumption is often very small. High power availability is important, even if the total energy consumption is not especially high. The range of power demand is

Figure 5. Examples of rural tourism with SAPS in northern Spain, from left to right: Refugi Estany Llong (Barruera, Lleida), Hostalet de Massivert (Malpàs, Lleida) *(Photos courtesy of SEBA)*

Figure 6. Examples of agricultural applications with SAPS in northern Spain, from left to right: Bizcarra y Salamaña and Montcaubo (both Zaidín, Huesca) *Photos courtesy of SEBA*

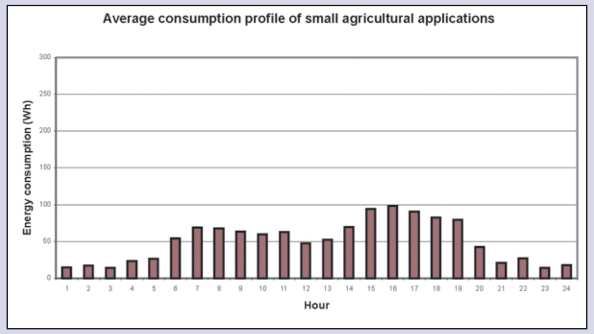

Figure 7. Typical load profiles encountered in small agricultural applications managed by the users association SEBA in northern Spain.

between 3 kW and up to 40 kW. In the case of residences with agricultural activities a typical load curve for residences are superimposed with the load curve of agricultural applications. In the study carried out in Spain an average of the specific load curve for agricultural applications could be filtered out with data from several sites.

Water pumping and treatment

Water pumping is needed for irrigation, but also for the supply of potable water. The electricity source has to be reliable, but short term fluctuations are not critical when water storage is used (in fact, this storage efficiently replaces the battery of the hybrid system). Normally water pumping concerns rather small loads. On the other hand, water desalination is becoming an important need mainly in countries with an arid climate. Typical small size potable water desalination systems for rural housings require around 400 W electrical power. Nevertheless bigger systems, up to 60 kW of power demand, is still within the size limitations set for this project. For these systems the clients are mostly municipalities and industry.

Communications

There is a wide spectrum of relay stations, from minimal installations (1 W) up to relay stations for mobile phones (10 kW-range). Often the latter ones are operated in DC (48 V) but require an inverter (2 kW) for the air conditioning system. Repeater stations require absolutely stable electricity supply. The load requirements change with the mode of operation (stand-by, receive, transmit, etc.).

Lighthouses

Lighthouses serve as navigational aid for the maritime traffic, operation mainly is during the night. The typical power lies below the scope of this study. Lighthouses are often located in remote regions at the coast and on islands. The remote location requires low maintenance energy supply with a high reliability. Hybrid systems for this product market combination therefore have to include a strong storage component. Such systems may avoid the need of the lighthouse keeper to live besides the lighthouse and thus reducing the operation cost of the light house.

High-cost grid connected customers (Segment A)

In order to assess the possible market for H-SAPS in this segment, power companies with "expensive" costumers were identified and contacted, to start with, in several regions of the countries of the project partners. All of the companies had customers in rural areas, mostly along the coast or in mountainous regions. There are at least three possible reasons for these customers to invest in SAPS generation; (1) The grid-connection is too expensive to maintain and operate for the grid-owner and no obligation to upgrade the connection and supply the "expensive" customers exists, (2) a segmentation of costs from the grid owner results in a high cost for these particular customers rendering SAPS and H-SAPS an attractive alternative or (3) the customer is not satisfied with the quality of the electricity supplied through the grid. In (1) a solution could be that the grid company installs SAPS generation, while in (2) and (3) the customer may decide to invest in a SAPS or H-SAPS.

In general the investigation of this market segment lead to the following results:

- The companies along the coast transmit electricity to islands, which causes high costs because of expensive sub-sea cables or long line suspensions. Furthermore, since the consumption on many of the islands is relatively small during the year, the cost per kWh transmitted becomes high.
- For inland companies the high cost of electricity was identified in sparsely populated areas. In these areas there are few and, in terms of power and energy demand, small customers per km of grid. For some companies the average number was below 10 customers/km, in some cases even as low as one household per transformer.
- A majority of the companies contacted explicitly stated that their policy for electricity distribution was to connect all customers in their region. Some of the companies explained this policy with a more equal distribution of costs and security of supply for all costumers.
- Only a small percentage of the companies had examined the actual costs for each customer group and high costs due to transmission to specific customers seemed to be an issue that was not prioritised.

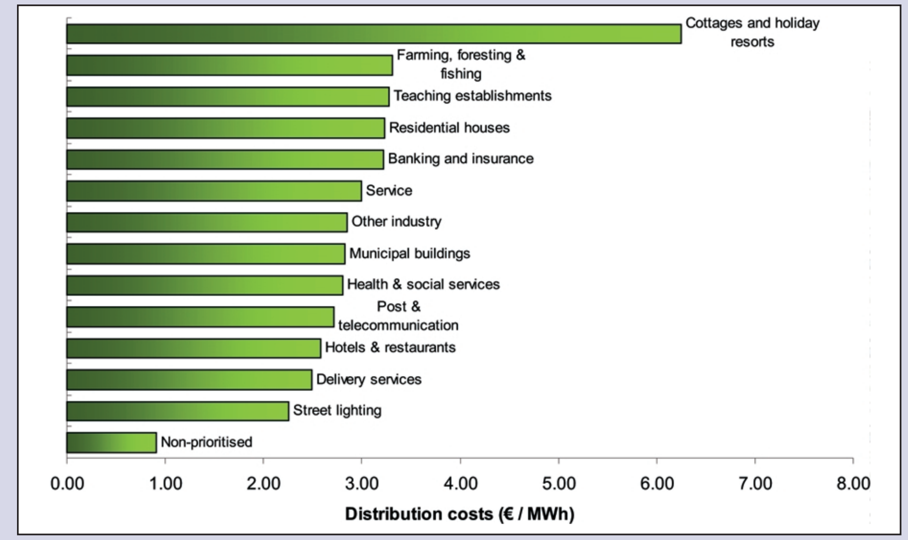

Figure 8. Typical electricity distribution costs for a Norwegian power company serving customers in a rural area. The distribution costs are categorised in different user categories.

In summary, a typical high-cost customer has been identified as being inhabitants on low-population island, mountain cottages and other holiday resorts. Figure 8 shows an example of distribution costs of a Norwegian power company. The user category: "Cottages and holiday resorts" has a distribution cost of about two times that of the second most expensive user group. A measure of the market for H-SAPS replacing grid-connection has, however, proven difficult to obtain partly because information on high-cost grid connected customer is held by local grid companies. In general we found that this market segment is small due to principles of equal distribution of costs. In addition, the trend towards grid-connected distributed generation (DG) by use of fossil fuel or local renewable energy sources in Europe may diminish the potential for H-SAPS in this market segment. This is due to reduction of energy losses, improvement of power quality and delay in upgrade and replacement of the electricity grid upon installation of DG in the grid.

Non-electrified customers and SAPS customers (Segments B and C)

In general the electricity grid is well developed in Europe and only about 300 000 residences is without grid-connection. These are mainly located in the former eastern block countries such as Romania where 45% of the population live in rural areas and 70 000 residences are without grid-connection. A large share of these residences, mainly connected to activities such as farming and forestry, are more than 10 km away from the main electricity grid. The annual electricity demand for these residences is generally very low (1200 kWh/yr). The potential for introduction of H-SAPS in these areas is, however, negligible (in the medium term; 10-15 years) due to factors like purchase power and political framework for introduction of renewable energy for electricity generation and grid-extension.

In the Nordic (Norway, Sweden, Denmark, Finland, Iceland, Greenland) and the Baltic countries, the electricity grid is well developed and close to 100% of the customers are connected to the electricity grid. In Norway only a handful of residences are without grid-connection. A more interesting market segment is the around 350 mountain tourist cabins/small hotels (rural tourism), which are not electrified. The potential market for replacement of conventional SAPS is perhaps greater. Weather and research stations in arctic regions, like on the island of Jan Mayen, Bear island and Svalbard constitutes a possible marked for H-SAPS. These are pristine areas where the potential for environmentally benign power and energy generation is more appreciated. The Svalbard islands as a whole has more than 3000 inhabitants and electricity and heat is presently generated and distributed from an old coal fired power plant.

A study done by NVE (Norwegian Water and Energy Directorate) showed, with reference to a newly built gas CHP power system for a remote residential building, that the break-even distance in terms of costs of grid connection and installation of SAPS in Norway is at approximately 2 km distance from the grid connection point. This is illustrated in Figure 9.

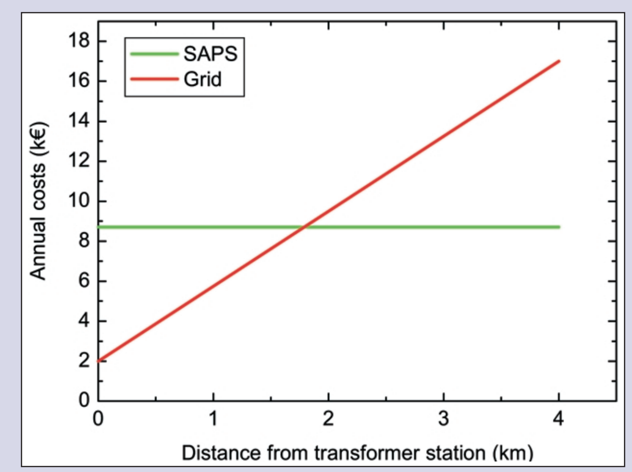

Figure 9. Annual costs of grid extension and installation of SAPS for a household in Norway.

It is estimated that 5-10 000 permanent dwellings in the UK are without electricity. Most of these are holiday homes. Furthermore, around 50 farm houses and 100 cottages on Exmoor has diesel generator sets as the only power and energy source.

Greece, being a country with a large island population, has some 19 000 permanently inhabited houses and 43 000 seasonally inhabited houses with no grid connection. For the case of Greece, a large part of the non-grid connected residences have a supply of heat and electricity by the use of conventional diesel generators. The island electricity grids in Greece are in general primarily powered by diesel generators. An estimation of the permanent population in this category is 10 000 people. During the summer months the population in these islands may be 2 to 5 times higher due to tourism.

It has proven difficult to get a total overview of the market for H-SAPS in Europe due to poor availability of rather scattered information. The list below, however, sums up the analysis on the market size for the different categories of users:

- Rural residences - Possibly the main market segment (see text above)
- Water pumping and treatment - 550 smaller systems (< 300 kW)
- Communications - 50 large systems (> 10 kW)
- Agricultural applications - 200 larger sites (> 20 MWh/yr)
- Rural tourism: Small market - 1500 sites with more than 20 MWh/yr

EVALUATION OF HYDROGEN TECHNOLOGIES FOR H-SAPS

Critical parameters of a hydrogen technology component, like cost, availability, reliability, etc, vary with size/capacity. It is therefore important to have an understanding of the size/capacity range of interest for hydrogen generation, storage and heat and electricity generation. On the generation side, this project is limited to 300 kW electric power. The capacity of hydrogen generation and storage in the system depends on the RES generation capacity and the electricity and heat demand of the user. The upper limits on the size are set on the basis of results from conceptual studies done in the high range (a few hundred kW) found in literature. For hydrogen production, storage and re-electrification of hydrogen upper limits of 120 Nm^3/h, 10 000 Nm^3 and 300 kW is set, respectively.

Hydrogen Production

In the context of H-SAPS, we focused only on hydrogen production through water electrolysis driven by RES. Electrolysis units installed in SAPS should have low idling power and short start-up times. The latter is less critical due to the decoupling of generation and load and the possibility of forecasting load and weather. The only technologies that meet the above limitations are Alkaline and Proton Exchange Membrane (PEM) electrolysers. The main disadvantages are that the cost of small electrolysers is still high partly as a result of immature technology and partly because the non-existence of a major market for small electrolysers. In figure 10, prices of electrolysers are presented for various suppliers.

Alkaline electrolysis is a well-established technology, while PEM electrolysis is presently expensive and not available on a commercial basis in medium to large scale (pre-commercial systems are available up to 10 Nm^3/h only). There is a trend to develop both alkaline and PEM electrolysers with a high output pressure of hydrogen, which is beneficial for SAPS as it reduces the need for expensive compressors, which also reduce the overall hydrogen system efficiency. PEM electrolyser are more compact and it is generally believed that PEM electrolysers have a potential for a higher output pressure (up to 200 bars). It is however likely that large medium- to large-scale electrolysis will be dominated by alkaline type electrolysers. An average cost of alkaline electrolysers were estimated to 8150 €/Nm^3/h.

Hydrogen Storage

Three different storage options were evaluated in H-SAPS project. These were storage of hydrogen as compressed gas, liquefied gas and in low-temperature metal hydrides. With regards to operation in a SAPS several critical parameters were evaluated.

Energy efficiency of the storage option is an important parameter because it influences the overall energy efficiency of the hydrogen system (electrolyser – storage – power generation). A hydrogen system with low energy efficiency will, depending on the correlation between renewable energy input and the load, result in the need for a larger storage unit, which again increases the cost and decreases the energy density of the system. Figure 11 shows approximate energy consumptions for the three storage options.

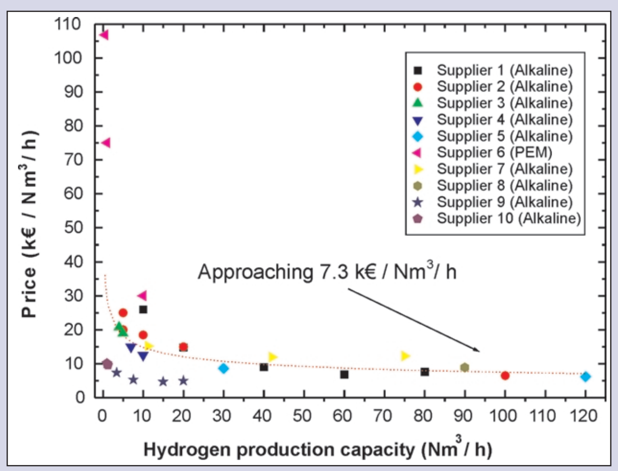

Figure 10. Prices of electrolysers as a function of hydrogen production capacity.

Figure 11 shows that nearly 1/3 of the energy content of hydrogen is consumed in order to cool down hydrogen to its liquid form. In addition, the storage of liquefied hydrogen is associated with losses of hydrogen due to boil-off. Boil-off losses originate from the need to keep the pressure at a constant level and may typically amount to 0.1% /day for larger cryogenic tanks (40-68 m^3). These are small values, but could prove significant for H-SAPS installations where energy is stored as hydrogen over longer periods of time.

In order to evaluate the comparative **costs** for the three different storage options European component manufacturers were contacted. A price/capacity diagram for commercially available steel storage tanks is shown in Figure 12.

From the price data shown in Figure 12 it may be seen that low-pressure storage solutions are not necessarily cheaper than the high-pressure ones. Price/capacity relations for smaller size compressed hydrogen and metal hydrides storage tanks is shown in Figure 13. In general, metal hydride storage options are expensive and available commercially only in small sizes (<20 Nm^3). In this project, cost of low pressure (20-30 bar) and high pressure (> 200 bar) conventional steel tank storage options were set to 38 and 45 €/Nm^3, respectively. The investigations of the cost of metal hydride storage solutions showed a large variation in price (790 - 25 000 €/Nm^3).

With respect to **response times,** compressed gas tanks may be charged and discharged rapidly. The response times for metal hydrides storage are, however, limited by heat transfer and kinetics of the hydride. A recent study (Yartys et al., 2003) shows that the commercially available metal hydride storage solutions have limitations in response times especially with regards to applications with a large flow-rate over size relation. Liquefaction plants for hydrogen have rather slow response times.

Safety is another important issue when introducing hydrogen gas handling in SAPS. However, the EU has recently approved 700 bar tanks for mobile application where the demand for compactness and low weight storage solution is significantly higher than for stationary applications. The use of liquefied hydrogen has long traditions and may be handled safely. Metal hydrides in generally considered a very safe storage solution because only ambient pressures and temperatures are needed.

Controllability and complexity of each hydrogen storage option are very important parameters that have to be taken into account for the introduction of hydrogen technologies in SAPS. Compressed hydrogen storage tanks can be easily monitored and are very simple to incorporate into a power system, while the introduction of liquefaction plant increases the complexity of such a system. On the other hand metal hydrides have an acceptable controllability, but the fact that a drying unit and heat integration is required, increases the complexity of the system.

Lifetime of both compressed hydrogen and liquefied hydrogen storage tanks is generally good, but with regard to liquefied hydrogen, boil-off effect may limit the overall storage period. The lifetime of metal hydride storage tanks is limited to a few thousand cycles, but recharging may be done by an elevation of temperature to around 200°C (AB5-type hydrides).

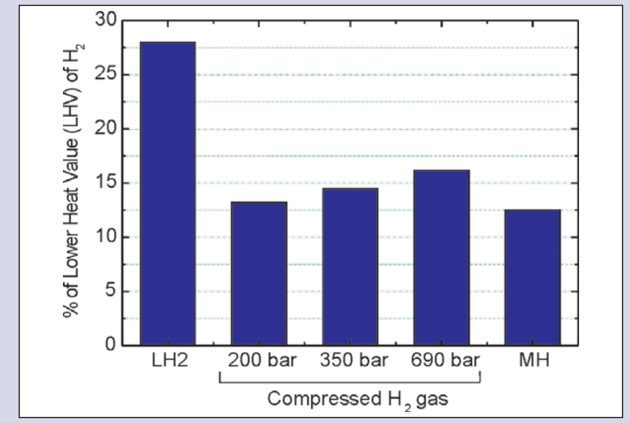

Figure 11. Energy consumption in % of lower heating value (LHV) of hydrogen gas for the different storage methods. MH - Metal hydride, LH_2 - Liquid hydrogen (Yartys et al, 2003)

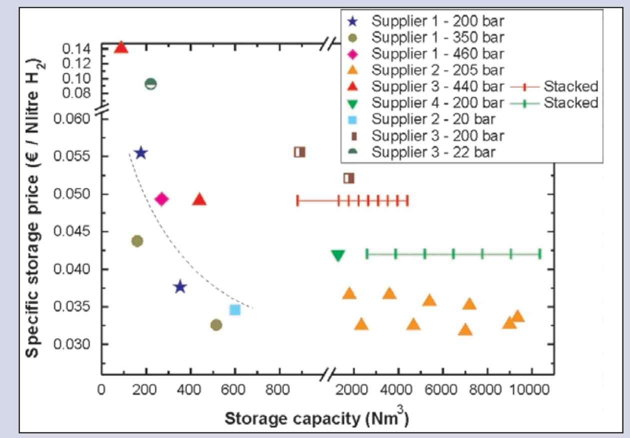

Figure 12. Price/capacity relations for commercially available compressed storage options for hydrogen in the medium- to large-scale range.

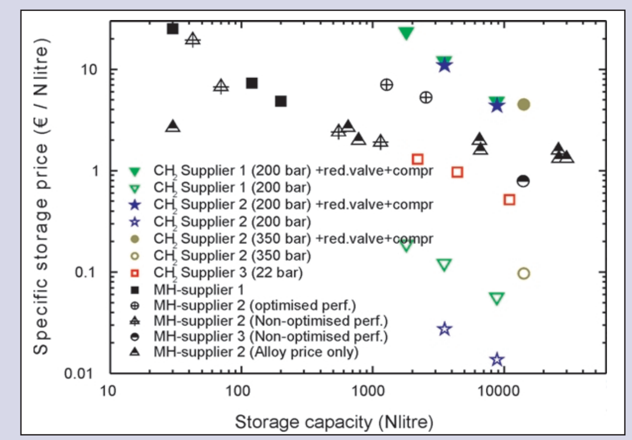

Figure 13. Price/capacity relations for small commercially available compressed hydrogen and metal hydride storage unit.

Figure 14. Metal hydride storage tank (Photo courtesy of Labtech Int. Ltd, Bulgaria)

Figure 15. A 5 kW PEM fuel cell developed by HELION Photo courtesy of HELION, France

Re-Electrification of Hydrogen

The potential power generation devices that utilise hydrogen that have been considered by the current study comprise fuel cells (PEM and Alkaline) and internal combustion engines (ICEs). Molten carbonate, phosphoric acid and solid oxide fuel cells were generally considered to slow at start-up and response because of the high operation temperatures.

PEM fuel cells have an operating temperature ranging from 50 to 100°C, they show fast response times and an overall efficiency between 40 and 50%. Pure hydrogen, which can be produced through water electrolysis driven by RES, can be used as a fuel and either air or pure oxygen as an oxidation media. With relation to their commercial status, the first commercial products in the range of 1-5 kW are already on the market. PEM fuel cells cost ranges between 6,000 and 10,000 €/kW. PEM fuel cells are per date not delivered with a lifetime warranty of more than 7000 hours, which gives an inadequate lifetime for most SAPS applications, which should be in the order of 40 000 hours.

Alkaline fuel cells operation temperature is 70-100°C. AFCs demonstrate good response times and an overall efficiency around 60%. They can also use pure hydrogen produced through water electrolysis as a fuel. Up to date AFCs have been used only in space applications and some pre-commercial prototypes. The main advantage of alkaline fuel cells over the PEM type is the low cost. In fact, recently (2003) manufactures of alkaline fuel cells have stated that the materials cost of the fuel cell stack may be less than 200 €/kW (Hodkinson, 2003).

Internal Combustion Engines running on hydrogen reach an electrical efficiency of up to 35% and have a higher potential for Combined Heat and Power applications than the low-temperature fuel cells. Hydrogen ICEs have a lower cost and higher reliability compared to fuel cells, but they show significantly lower efficiencies than fuel cells, results in a need for a larger hydrogen storage tank and hydrogen generation unit, which are main cost factors for SAPS with hydrogen as an energy carrier. Their price is also fairly high (2,000 - 3,000 €/kW) compared to diesel generator sets.

MARKET ANALYSIS: THE SUPPLY SIDE

Main actors of the market

The supply side of the market can be divided into two main groups: 1) the operational market actors and 2) the visionary market drivers. This division and their different roles are briefly explained in the following:

1) The development of a hydrogen related market for which the technology is not expected to become mature and cost efficient in the short term (next 5-10 years) cannot rely on cost-benefit incentives or profit driven business decisions from the average commercial actor. This will particularly be the case for smaller technology developers that cover the various bits and pieces of more complex energy systems involving hydrogen. Without clear commercial incentives on a short term, these market actors will not produce results at a very high speed.

2) Consequently, the long-term hydrogen related market developments must rely on the large, long-term and visionary market drivers. i.e. huge energy companies with objectives reaching well into the next 2-3 decades, both with regard to commercial achievements as well as their responsibilities vis a vis the society. Companies such as SHELL, BP, NORSK HYDRO etc have real impact in the market place and when these huge actors go public with their visions for the development of a hydrogen economy, the market will listen. There will always be more detailed strategies and work programmes to substantiate these visions. These work programmes will be based on scenarios and shorter-term actions/funding for technology and market developments, giving the technology suppliers sufficient incentive and prospects for short-term cost/benefit and profit.

Technology introduction criteria

The project has identifies some important criteria for the introduction of Hydrogen Stand-Alone Power Systems. These are listed and explained below:

- Component availability
- H-SAPS technology companies and joint ventures
- Trained O&M staff
- Market size awareness
- Available funding
- Previous H-SAPS experience (demonstrations)

Component availability. All components comprising a hydrogen stand-alone power system must be available by respective providers. After-sales support by agents or installers of hydrogen technologies is also an important factor.

Alkaline electrolysis is a well established technology since 1940s, therefore lifetime experience has been obtained and providers give good warranties. In Europe there are around 10 companies providing alkaline water electrolysis units. On the other hand, PEM electrolysers are available only in pre-commercial basis and there are just three companies providing such units in Europe. There is limited lifetime experience on PEM electrolysers, thus no or only short-time warranties are given. In addition, they are only available in small scale (< 10-20 Nm^3/h) and their prices range from 3 to 10 times higher than alkaline electrolysers.

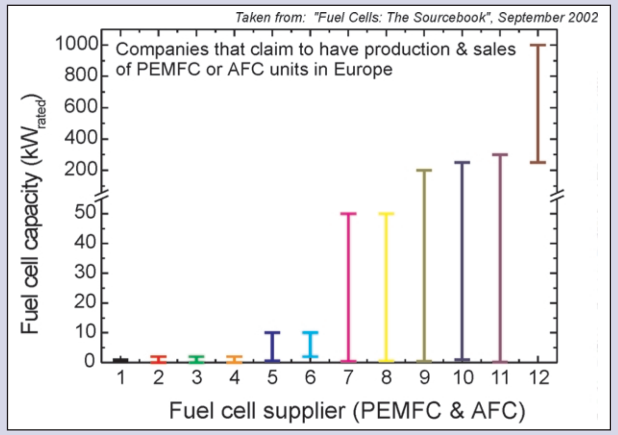

Figure 16. Fuel Cells availability

Regarding fuel cells availability, 12 European companies are claiming production and sales of AFC or PEMFC units in the range of 0.1-300 kW, but the availability of units with capacity greater than 10-20 kW is limited. In addition, lifetime warranties are poor even for small systems. In Figure 16 availability of fuel cells in Europe is shown.

Internal Combustion Engines (ICE) than run on natural gas may be easily converted to hydrogen operation and therefore bought from companies delivering ICE's for natural gas. There are also some manufacturers of dedicated hydrogen ICEs worldwide. At present, there is no market for Hydrogen ICE's and there is a limited lifetime experience on this technology.

With relation to hydrogen storage technologies, compressed hydrogen storage is an available and already proven technology. Metal hydrides are available, but only in smaller sizes. It is likely that metal hydride storage solution may play a role for smaller specialised H-SAPS solutions, such as smaller emergency power units or sender stations. In these applications metal hydrides may compete in price with compressed hydrogen storage because of the compactness the fact that compression is obtained with the supply of heat only (no need for a compressor).

Market size awareness. One has to have a certain knowledge of the H-SAPS market in order to start investing in development or commercialisation of H-SAPS systems or dedicated H-SAPS components. Unfortunately there are no European market studies currently available that could help determine the market size even for conventional Stand-Alone Power Systems.

Hydrogen Stand-Alone Power Systems companies and joint ventures. To introduce hydrogen in the market of SAPS, Hydrogen Technology providers and Hydrogen SAPS installers and/or agents must exist. During the H-SAPS market analysis, many companies active in the field completed questionnaires and certain people of these companies were interviewed. According to the results of this survey, a handful of Fuel Cells companies mentioned H-SAPS as one of several entry markets. Among these there were one company with primary focus on the commercialisation of small H-SAPS.

Available funding. Hydrogen technologies are currently at research and development phase and are 5-10 years away from being commercial. To promote the introduction of such technologies in conventional Stand-Alone Power Systems and remove economic barriers of an entirely new market, national or local governments and industry should provide greater funding to help the realisation of real-scale hydrogen systems. Until recently, there was a lack of demonstration project funding and focus was only on basic research and development of hydrogen technology components.

Trained O&M staff. Reliable operation and maintenance of hydrogen systems must be ensured, since currently there is no dedicated training for this market segment. H-SAPS introduces gas handling of an explosive gas into an area, which has been dominated by electrical engineering.

Previous H-SAPS experience. Successful realisation of real-scale Hydrogen Stand-Alone Power Systems and experiences that will be gained from these systems will result in removal of technical and economic barriers for the introduction of Hydrogen Stand-Alone Power Systems in the market. At present H-SAPS has been demonstrated in around 10 demonstration plants in Europe. Most of these comprise solar electricity as the renewable energy input and the range in size from 1 to 10 kW. The main focus for almost all of these demonstrators has been the connection between the PV array and the electrolyser. Wind as a renewable energy source has been getting increased attention in the last few years and, as experience is gained on the production of hydrogen from fluctuating energy sources, quite a few H-SAPS demonstrators are presently in the planning or in the installation phase.

CASE STUDIES

The uniqueness in the present market analysis is the basis on technology and market parameters from stand alone power systems in operation in the present European SAPS markets rather than theoretical assumptions. In order to assess the technological and economical potentials and limitations for hydrogen energy technology in a single installation perspective, a categorisation of existing SAPS, based on climate, renewable energy source and system size was undertaken.

The project partners (TTA, Econnect, IFE and CRES) are all involved at one or more stages of the installation of SAPS; planning, installation, operation. From the portfolio of these companies, representing four climatically different parts of Europe, five existing SAPS systems were chosen. These cases were analysed by computer simulation of different technological solutions on how diesel generators and batteries can be substituted by hydrogen energy technology. A description of the different cases chosen is given in Table 2.

Modelling tool

The modelling has been done with TRNSYS, which is a transient systems simulation program with a modular structure. The standard TRNSYS library includes many of the components commonly found in thermal and electrical renewable energy systems, as well as component routines to handle input of weather data. Models for renewable energy and hydrogen technology components have been added to TRNSYS through the so-called HYDROGEMS library developed at IFE (www.hydrogems.no). In the TRNSYS/ HYDROGEMS a model of a conventional SAPS or H-SAPS may be constructed by choosing the components from the libraries and connecting them together just like for a real system.

Table 2.
Description of the five existing SAPS chosen for energy-flow modelling of the introduction of hydrogen technology for energy storage.

Case No.	Site	Technology	Maximum power demand)
1	Kythnos	Diesel-battery mode	~8 kW
2	Fair Isle	Wind-diesel	~100 kW
3	Rum	Hydro run-off-diesel	~70 kW
4	Rauhelleren	Diesel only	~30 kW
5	La Rambla del Agua	PV-battery-seasonal	~11 kW

Table 3.
Short description of the models used to model each component in the energy systems.

Component	Type
WECS	Small synchronous machines - power profile given specifically for each case
Micro-hydro	Run off river - type
PV-modules	Standard commercial systems
Electrolyser	Alkaline - 30 bar outlet pressure
Fuel Cell	Pressurised (3 bar) Polymer Exchange Membrane (PEM)-type
Hydrogen storage unit	Compressed gas - steel cylinders (30 bar)
DEGS	Standard commercial systems

Technical assumption

In order to evaluate the available hydrogen technology and its potential for use in H-SAPS, it is important to limit the size range of components to include changes in technology with size/capacity. In this project a limitation of a few hundred kW is set on the power output for the H-SAPS system. We have chosen to limit the power generation side to 300 kW. The size/capacity of the other hydrogen technology components are dependent on the renewable energy sources and the electricity and heat load given for a specific application. For hydrogen production, storage and re-electrification of hydrogen upper limits of 120 Nm^3/h, 10,000 Nm^3 and 300 kW are assumed, respectively.

The components used in the models are briefly described in Table 3.

Table 4.
Cost model assumptions used in the techno-economic modelling. A system lifetime of 30 years and an interest rate of 7% p.a. are used.

Component description	Cost model validity range			Cost fit parameters		Life-time	O&M
Component	From	To	Unit	A	B	yrs	% of investment
WECS	15	200	kW	0	1,400	30	1.5
Micro-hydro	15	35	kW	0	2,400	20	1.5
PV	0	inf	kW	0	6,750	30	0.0
Electrolyser	2	120	Nm^3/h	0	8,150	20	2.0
H_2-storage unit	5	10,000	Nm^3	0	38	20	0.5
Fuel cell	5	50	kW	0	3,000	10	2.5
Battery	0	1,000	kWh	0	100	7	1.0
DEGS	5	50	kW	6,000	140	6	2.0

Table 5.
Present and future costs for the hydrogen energy system components

Hydrogen technology component	Type	2003-5			Long-term (2020)		
		Lifetime (yrs)	O&M (% of inv.costs)	Cost	Lifetime (yrs)	O&M (% of inv.costs)	Inv. cost
Electrolyser	Alkaline (>30 bar outlet pressure)	20	2.0	8,150 €/Nm^3/h	20	1.0	4,075* €/Nm^3/h
Fuel Cell	PEM	10	2.5	3,000 €/kW	20	1.0	300♣ €/kW
H_2-storage unit	Compressed gas (low-pressure 20-30 bar)	20	0.5	38 €/Nm^3	20	0.5	25♠ €/Nm^3

* A 50% reduction in cost is assumed.
♣ EU-target cost for stationary applications in the long-term.
♠ 30-40% reduction in cost assumed by the steel tank producer Holger Andreasen GmbH, private communication.

Economic assumptions

In the economic assessment for each of the modelled cases, investment costs, Operation and Maintenance (O&M) - costs and fuel costs are included. The cost data have been collected by use of questionnaires to industry in Europe and the USA in the period 2001 to 2003 (see previous section: "Evaluation of technology for H-SAPS"). The overall energy system is given a lifetime of 30 years and based on lifetime, O&M and investment costs of each component the present value are calculated for each component. By introducing discounted costs, the extra investments for replacing a component after its economic lifetime has expired, is included. The cost of energy (COE) is calculated based on annuity calculation on the present value for each component and the average annual energy production from the system. Table 4 lists the economic assumption for each component.

The costs of inverters and converters are assumed to be included in the costs of the components either generating or consuming electricity.

In order to estimate the future competitiveness of hydrogen technology in SAPS, extrapolation of the costs of hydrogen technology has been done. The present and future cost assumptions are summarised in Table 5.

Modelling results

A comparison of the cost of energy for the conventional SAPS and H-SAPS in the short (2003-2005) and long term (2020) for all simulated cases is given in Figure 17. No change in time of the price of conventional technology is introduced in this picture. Conventional technology like batteries and DEGS is believed to have a limited cost reduction potential. Furthermore, the CO_2 taxes on diesel fuel are believed to increase in the long term. The economic results from the modelling should be interpreted with caution, as they are highly site specific. The results should therefore just be treated as indicative. Figure 17 shows that for the chosen sites, the cost of energy (COE) for the hydrogen energy system ("H2-long term") is indicated to be competitive with a conventional system ("Ref. case (2003)") for the two PV-module based energy systems chosen. This stems from a good match between power generation and electricity demand for these systems. In fact, both of these sites have excellent solar resources and low nighttime loads because of their Mediterranean location. In short, the need for energy storage is defined on a weekly rather than on a seasonal basis.

Rauhelleren and the islands of Rum and Fair either have micro-hydro or wind generation. The energy storage demand for these systems are significantly larger than for the described PV-based systems. These are, in the estimates of Figure 17, seen not to be competitive with conventional generation in the long-term. This is due to the seasonal characteristics of the load and hence the seasonal characteristics of the energy storage.

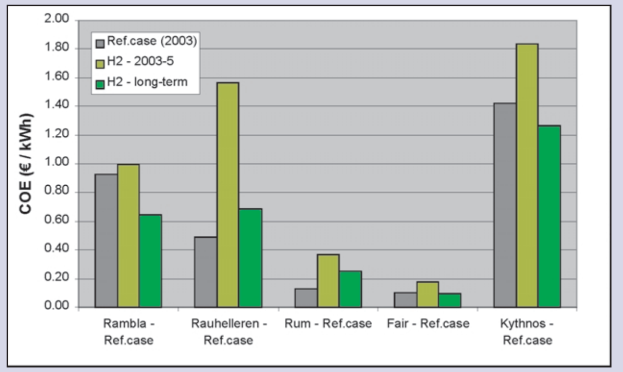

Figure 17. Comparison of the cost of energy (COE) for the conventional SAPS and HSAPS in 2003-5 and in the long-term for the 5 simulated cases.

SUMMARY AND POLICY RECOMMENDATIONS

Market size and technology

An estimate of the market potential for the introduction of hydrogen technology in stand-alone power systems has been difficult to obtain. However, some market niches in rural areas, such as rural tourism, rural farming, holiday resorts, etc. have been identified. The hydrogen technology for production and storage of hydrogen is mature but still expensive. Fuel cells for the production of heat and electricity are available on a pre-commercial basis, but the lifetime warranty is too short and the prices far too high in order for these solutions to be competitive. Internal combustion engines (ICEs) represent a transition technology for H-SAPS in the short-term. ICEs have lower energy efficiencies than fuel cells, which will limit the potential in energy systems were long term storage of energy as hydrogen is needed. Alkaline fuel cells may represent a promising and potentially far less expensive option. But it still remains to see if the expectations in price, lifetime and operability for alkaline fuel cells are met in the near future.

Specific case studies have been undertaken on five existing SAPS. These showed that the economy of the hydrogen solution is strongly dependent upon the site characteristics.

Market drivers

The long-term perspective implies that national governments and international public institutions must play a key role. However, the policies and limited public funds must support the strategies of the visionary market drivers. As Mr. Jeroen van der Veer, the President of Shell, expressed in his speech at the 14th Hydrogen Conference in Montreal, Canada in June 2002.

"We believe long-term value in the hydrogen industry will be generated the same way as in other industries – through the development and application of competitive technologies and through access to resources and markets. Focus on the customer, in whatever part of the value chain, is what counts."

Expressed from anybody else but the President of Shell or his equals, this vision would not trigger the same belief in the forthcoming hydrogen markets. The authorities must therefore see these visionary market drivers as their closest allied and adopt their visions and strategies as the basis for their policy making.

Local energy planning

As the study of the demand side shows, the key-information required for assessing the H-SAPS potential is practically non-existing at local level. Consequently, it is even more difficult to assess potential at more aggregated levels.

The work undertaken by the H-SAPS project to identify load profiles of individual customers is a step in the right direction, but it is crucial that such load profiles are in conformity with the local level energy planning requirements.

Policies should put more emphasis on the role to be played by local energy planning in designing the various energy markets at local level, including the HSAPS market. By establishing frameworks and routines for collecting and assessing data, which are useful for energy market development at local level, the local utilities, and market actors could benefit from better knowledge of the customers needs and market perspectives.

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