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ALTENER Programme

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.

H-SAPS

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

http://www.hsaps.ife.no

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 XVII, the European Commission's Directorate-General for Energy. Its main role is to help create an appropriate environment for the Community Strategy and Action Plan for renewable energy sources. The programme will also encourage 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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ΚΑΠΕ
CRES

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.

TABLE
Results of SWOT analysis

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 electrolyser 4. Lack of aftersales support 5. Procurement cost 6. Lack of component and system lifetime 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

INTRODUCTION

A large number of stand alone power systems (SAPS) are 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, 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 near future.

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) and 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 establish a broad understanding of the technical and economical market potential for H-SAPS that are based on local renewable energy sources. Secondly, to 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. Thirdly, to identify the legal, regulatory and administrative hurdles for the HSAPS market development and draw the attention of authorities towards amending such problems. Lastly, to propose a roadmap for demonstration projects for HSAPS installations.

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

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 houses have no access to the grid. These are mainly located in remote areas such as islands or mountain regions. The market for HSAPS 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 diesel generation is given in Table 1 for the case of Norway.

TABLE 1.
kWh costs for electricity generation 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:

- ✔ Frequency control – stability
- ✔ Fluctuating generation & load
- ✔ Long term energy storage
- ✔ Security of supply
- ✔ Low renewable energy penetration
- ✔ Energy dumping
- ✔ Load growth

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

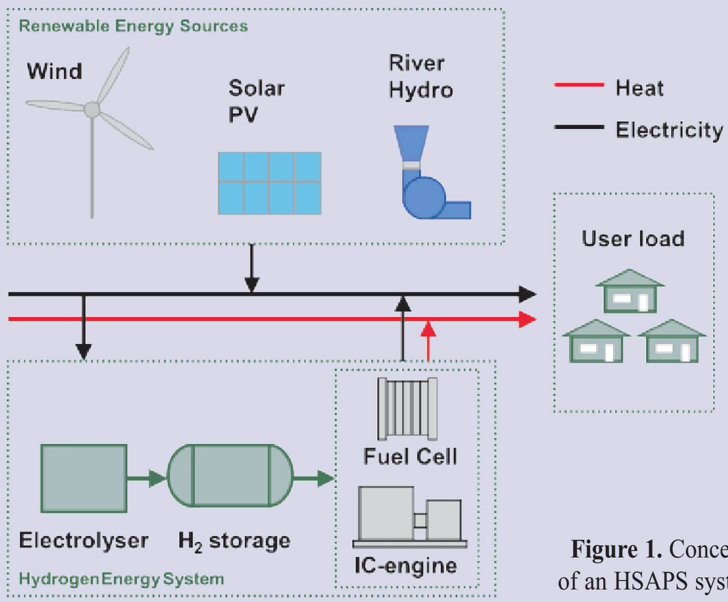

Figure 1. Concept of an HSAPS system

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 continuous 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 / spinning reserve:
- 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, low O&M, environmentally benign, way of storing energy and to increase the renewable energy penetration even to 100%.

MARKET IDENTIFICATION – THE DEMAND SIDE

Demand orientation

The future demand of SAPS as well as its preferred characteristics depend on the present status of the SAPS technologies and its prospects. This is the why in the context of the current study the knowledge SAPS users have of hydrogen technology and their potential use to improve the characteristics of their systems was studied. The current and future market for HSAPS, comprises high-end cost segments of customers connected to an electricity grid (segment A), customers with a conventional SAPS solution (segment B) and customers with no grid connection (segment C).

Segment A

In order to assess the possible market for HSAPS described by Segment A power companies with possible costumers were contacted in several regions. All showed the same potential costumer profiles and in all countries studied similar results have been obtained.

Situation:

- All of the companies were operating in rural areas, mostly along the coast and far north in Norway and other European areas
- The companies along the coast transmit electricity to islands, which causes high costs. This is because connection of the islands to the mainland grid normally is done by using expensive subsea cables. Since the consumption on many of the islands is relatively small during the year, the costs per kWh transmitted are very high.
- For inland companies the high costs were due to that most of the area is sparsely populated. There are few customers per km of grid, for some companies the average number is actually below 10 customers/km. Many of the companies also had few customers, as low as one household per transformer.

Results:

- None of the companies had examined the actual costs for each customer or cluster of customer (if several households were located on the same island or in the same remote region on the mainland). High costs due to transmission to specific customers seemed to be a problem that was not prioritised.
- A typical high-cost customer has been identified as being the cottages and holiday resorts and a total annual consumption can be associated with this user group.
- All the companies contacted had 100% of their customers connected to the grid and hence no customers were operating SAPS. Most of the companies had not considered installation of SAPS. Most of the company contacts explicitly stated that their policy for transmission of electricity is that every customer in their region should be connected to the grid. Some of the companies explained this policy with equity, costs, and security of supply.

Conclusions:

- Estimating the number of households with a potential demand for electrification in this segment is very difficult.
- Estimating the energy and power demand of so-called high-cost grid customers would probably involve significant efforts, as information, if available at all, is held by local net companies. Nevertheless, as conclusion from the current study it can be said that the market potential in this segment is very low.

TABLE 2.

Customer categorisation, annual energy consumption and electricity price for the Skjerstad power company

User category	Electricity price (EURO / MWh)	Energy consumption (MWh) (for 2000)
Non-prioritised	0.91	121
Street lighting	2.26	428
Delivery services	2.49	571
Hotels and restaurants	2.58	228
Post and telecommunication	2.72	9
Health and social services	2.80	600
Municipal buildings	2.83	195
Other industry	2.85	258
Service	3.00	2402
Banking and insurance	3.22	38
Houses	3.23	9947
Teaching establ.	3.28	804
Farming, foresting, fishing	3.31	1126
Cottages and holiday resorts	6.25	1194

Example: Skjerstad power station in Norway. Table 2 presents an overview of user category, electricity price and energy consumption for a total of 13 user categories.

Segment B and C

These segments were treated together as the potential demand is very similar and H-SAPS has in any way to be compared to conventional SAPS. Because the user, in most cases, is interested in the service and not in the technology, detection of the market for SAPS is really difficult if the different applications for which power is required is not taken into account.

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 marked 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

Figure 2. 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*

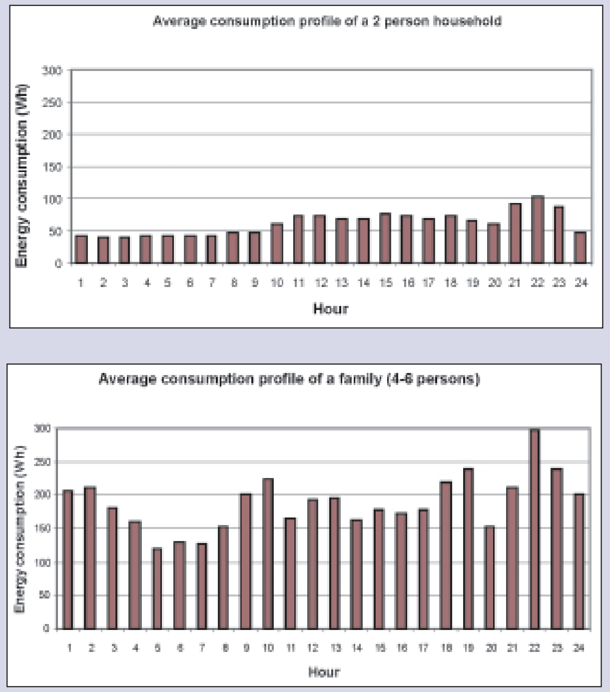

Fig. 3 and 4: Typical load profiles encountered in SAPS installations managed by the users association SEBA in northern Spain.

encountered is between 600W 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.

Rural tourism

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

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

Often rural tourism is characterised by a punctually strong electricity demand, caused by kitchen and restaurant services. The power range encountered is between 2kW and 20kW. 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 specially high. The range of power demand is between 3kW 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 a 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 400W electrical power. Nevertheless bigger systems until 60kW of power demand can be still market for SAPS. For these systems the clients are basically municipalities and industry.

Communications

There is a wide spectrum of relay stations, from minimal installations (1W) up to relay stations for mobile phones (10kW-range). Often the latter ones are operated in DC (48V) but require an inverter (2kW) 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.).

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*

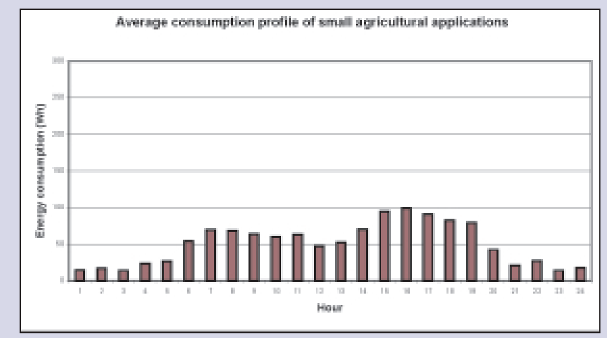

Figure 7: Typical load profiles encountered in small agricultural applications with SAPS installations managed by the users association SEBA in northern Spain.

EVALUATION OF HYDROGEN TECHNOLOGIES SUITABLE TO MEET THE DEMAND OF SAPS

All systems examined in the framework of H-SAPS had a total nominal capacity for power generation of up to 300 kW. The capacity of the hydrogen technologies for any application depends on the RES generating capacity on one hand and the electricity and heat demand on the other. The exact capacity of hydrogen production, storage and re-electrification technologies is site-specific and can only be determined following an optimisation procedure aiming to minimise a specific parameter like the cost of kWh of a system.

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 not use much idling power and have short start-up times. The latter is less critical due to the decoupling of generation and load and the possibility of forecasting load/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 and no major market for small electrolysers exists.

In figure 9, prices (per Nm³/h) of electrolysers are presented for various suppliers.

Comparing the two different electrolysis technologies we may conclude that alkaline electrolysis is a well-established technology, while PEM electrolysis is a promising one still facing some difficulties to overcome: 1) Few PEM electrolysis manufacturers exist on the market, 2) there are little lifetime experience and modest lifetime warranties.

Hydrogen Storage

Three different storage options (compressed hydrogen, liquefied hydrogen and low temperature metal hydrides) were evaluated in H-SAPS project. With regards to operation in a SAPS the following storage option parameters were examined:

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 10 shows approximate energy consumptions for the three storage options.

Figure 10 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 attended 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 account as about 0.1% / day of the hydrogen content in larger cryogenic tanks (40 – 68 m³). These are small values, but could prove significant for HSAPS installations where hydrogen is covering a seasonal energy storage need. In this case the accumulated boil-off losses may reduce the overall energy efficiency and hence the storage capacity demand even further.

Costs. In order to evaluate the comparative costs for the three different storage options European component manufacturers were contacted. The list of manufacturers is by no means exhaustive, but the main actors are believed to be included. The list is obtained from Norsk Hydro. A price/capacity diagram for commercially available steel storage tanks is shown in Figure 11.

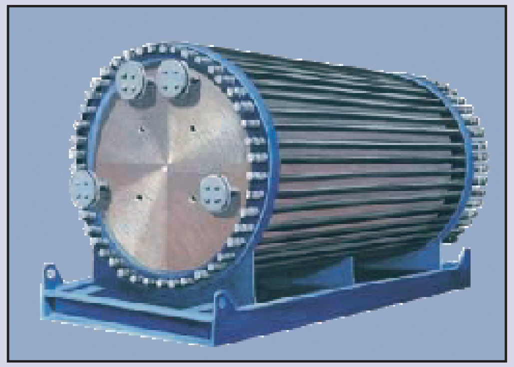

Figure 8.
Cell stack of water electrolysis unit.

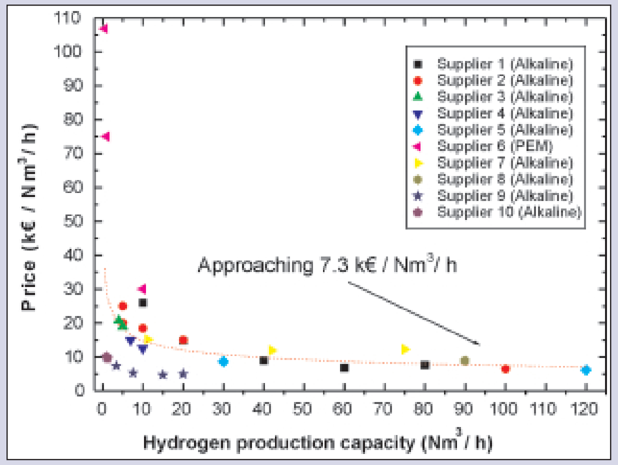

Figure 9. Prices of electrolysers as a function of hydrogen production capacity.

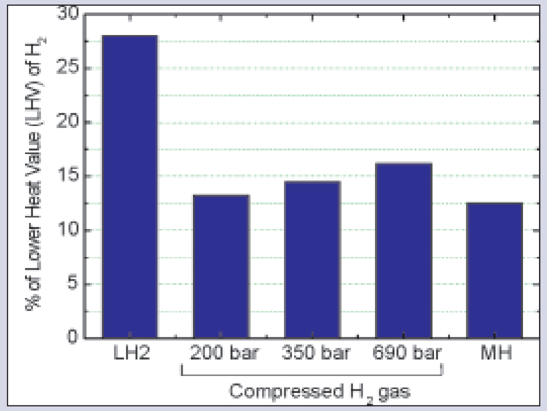

Figure 10. Energy consumption in % of lower heating value (LHV) of hydrogen gas for the different storage methods. MH – Metal hydride, LH2 – Liquid hydrogen (Yartys et al, 2003).

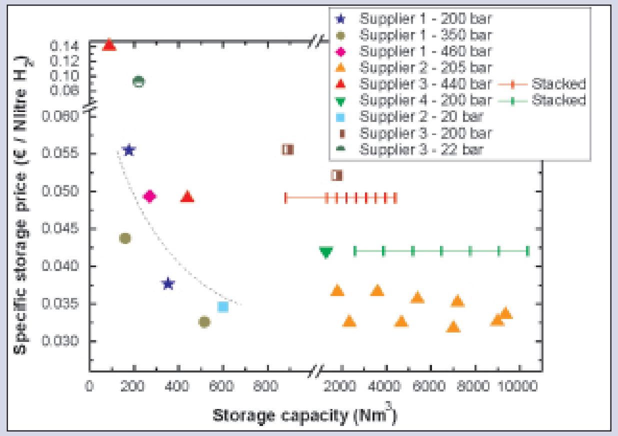

Figure 11. Price/capacity relations for commercially available compressed storage options for hydrogen in the medium- to large-scale range. The dotted line shows the fit used in the techno-economic assessments used for medium scale storage tanks.

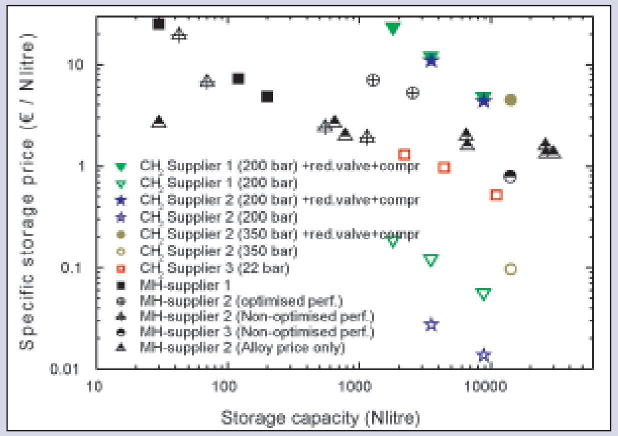

Figure 12. Price/capacity relations for small commercially available compressed hydrogen and metal hydride storage unit.

Figure 13. Metal hydride storage tank
(Photo courtesy of Labtech Int. Ltd, Bulgaria)

Figure 14. A 5 kW PEM fuel cell developed by HELION
Photo courtesy of HELION, France

From the price data shown in Figure 11 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 can be seen in Figure 12, where for all sizes of the high pressure tanks, a diaphragm type compressor with a hydrogen flow-rate high enough to compress hydrogen from a ~6 kW electrolyser (operated at maximum power – 4 kWh/Nm³ assumed) has been chosen.

With relation to **response times,** compressed hydrogen charge and discharge times are acceptable, metal hydrides response times have a limit which may be critical for applications where size: flow rate ratio is low such as in back up systems, but these were not included in our study. Liquefied hydrogen has a very slow response time when charging.

Regarding **safety,** which is another critical parameter for hydrogen storage, high pressure compressed hydrogen tanks up to 350 bar are considered generally safe and this is also the case for metal hydrides and liquefied hydrogen.

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 liquefied hydrogen 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 must also be installed 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 overall storage period. On the contrary, lifetime of metal hydrides' storage tanks is considered very limited.

The analysis of different hydrogen storage options examined in the context of H-SAPS showed that compressed hydrogen storage is the best alternative, at least in the short term.

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).

PEM fuel cells have an operating temperature ranging from 50 to 100ºC, 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, first commercial products in the range of 1-5 kW are already on the market. PEM fuel cells cost ranges between 6000 and 10000 €/kW.

Alkaline fuel cells operation temperature is 70–100ºC. AFCs demonstrate good response times and an overall efficiency around 60%. They also can 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 have been introduced to the market. Alkaline fuel cells have a low cost, are very simple and show a very good cathode performance. In addition, no exotic materials needed to produce alkaline fuel cells.

Internal Combustion Engines running on hydrogen reach an efficiency of up to 35% and have a higher potential for Combined Heat and Power applications. Hydrogen ICEs have a lower cost and higher reliability compared to fuel cells, but on the other hand, the fact 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 (2000–3000 €/kW) compared to diesel gensets.

MARKET ANALYSIS: THE SUPPLY SIDE

Main actors of the market

Hydrogen power systems are currently not considered as a mature technology, therefore one should study carefully the main actors of the market and the solutions they are capable to provide to their customers. The most important actors of the market of hydrogen stand-alone power systems are:

- Complete system providers
- Primary components providers
  - Renewable energy providers (Wind Turbines, Photovoltaics, Micro-hydro, Wave Energy, Geothermal Energy etc.)
  - Hydrogen technology providers (Fuel Cells, Hydrogen ICE's, Hydrogen Microturbines, Electrolysers, Hydrogen storage units)
- BOP providers
  - Control system
  - Inverters
  - Compressors
  - Pumps
  - Equipment for "plumbing" and assembly

Some criteria for the introduction of Hydrogen Stand-Alone Power Systems to the real market are the following:

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.

The current situation regarding component availability for each hydrogen technology is as follows:

With regards to hydrogen production in HSAPS, focus was only given in alkaline and PEM water electrolysis, as mentioned before. Alkaline electrolysis is a well established technology since 1940s, therefore lifetime experience has been obtained and providers give good warranties. In Europe there are 10 companies providing alkaline water electrolysis units. For units with capacities up to 120 Nm^3/h, alkaline electrolysis units' price is approximately 7300 €/Nm^3/h. On the other hand, PEM electrolysers are available only in pre-commercial basis and there are just three companies providing such units all around Europe. There is limited lifetime experience on PEM electrolysers, thus warranties are given for short periods of time. In addition, they are only available in small scale (< 10-20 Nm^3/h) and their prices are considerably high (30 000 –100 000 €/Nm^3/h).

Regarding fuel cells availability, 12 European companies 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, warranties are poor in the range of 10-20 kW. For smaller units warranties are approximately 5000 hours of operation. Fuel cells prices range from 6,000-10,000 €/kW. In Figure 15 availability of fuel cells at European level is shown.

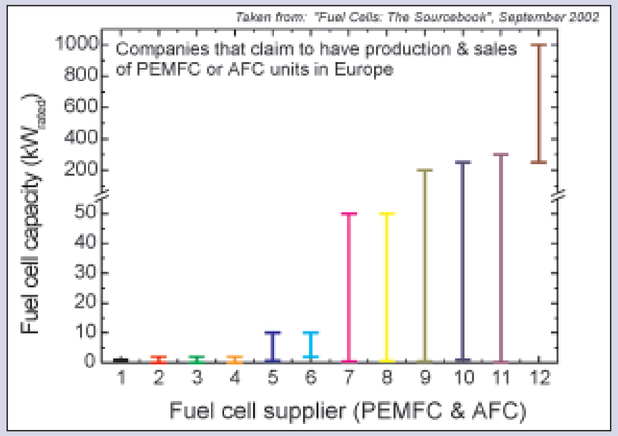

Figure 15. Fuel Cells availability

There also exist Internal Combustion Engines at 0-300 kW range running on natural gas which can use hydrogen as a fuel, too and some dedicated hydrogen ICEs manufacturers. Today there is no market present for Hydrogen ICEs and there is 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 on a pre-commercial scale and they are available only in small scale (less than 20 Nm^3). On the other hand metal hydrides prices are variable, but still remain high, ranging between 790 and 25000 €/Nm^3.

Market size awareness. One has to know the exact size of this market in order to start investing on these technologies. At least a draft estimation of the market size is always necessary for investors. Unfortunately there are no currently available European market studies to help determine the market size not only of Hydrogen Stand-Alone Power Systems, but even for conventional Stand-Alone Power Systems.

Hydrogen Stand-Alone Power Systems companies and joint ventures. To introduce hydrogen in the market of Stand-Alone Power Systems, Hydrogen Technology providers and Hydrogen SAPS installers and/or agents must exist. During the HSAPS 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 HSAPS as one of several entry markets. Among these companies there is one with primary focus on small Hydrogen Stand-Alone Power Systems.

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 given 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.

Previous HSAPS 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.

CASE STUDIES RESULTS

The uniqueness in the present market analysis is that it is based 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 where undertaken. The following parameters were included:

- Rotating machine (R) or inverter (I) dominated system
- Storage (Stor) or no storage (NoSt)
- Stochastic (Sto) or deterministic (Det) primary energy

Load profile and load management were seen as secondary parameters in the analysis. 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 Table 3.

TABLE 3.

Description of the five (5) existing SAPS chosen for energy-flow modelling of the introduction of hydrogen technology for energy storage (R – Rotating machine, I – Inverter, Stor – Energy storage, NoSt – No energy storage, Det – deterministic primary energy, Sto – Stochastic primary energy)

Category	Site	Technology	Maximum power demand
R-Stor-Det	Kythnos	Diesel-battery mode	~8 kW
R-noSt-Sto	Fair Isle	Wind-diesel	~100 kW
R-noSt-Det	Rum	Hydro run-off-diesel	~70 kW
R-noSt-Det	Rauhelleren	Diesel only	~30 kW
I-Stor-Sto	La Rambla del Agua	PV-battery-seasonal	~11 kW

Modelling tool

The modelling has been done with TRNSYS. TRNSYS 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 or other time-dependent forcing functions. The modular structure of TRNSYS gives the program the desired flexibility, as it facilitates for the addition of mathematical models not included in the standard library. The program is well suited to perform detailed analyses of systems whose behaviour is dependent on the passage of time. The HYDROGEMS library includes models for power producing equipment, such as photovoltaic (PV) generators, wind energy conversion systems (WECS), diesel engine generator systems (DEGS), proton exchange membrane fuel cells (PEMFC), and alkaline fuel cells (AFC). Models for water electrolysis and H2-storage are also included, along with models for a lead-acid battery and power conditioning equipment. The models have been designed to be as generic as possible. That is, the models are designed so that specific components characteristics obtained from manufacturers, or from experiments, readily can be added to a database. In general, component specific parameters, such as those describing current-voltage characteristics (IU-curves), are read from an external file, while design parameters, such as number of cells in series and/or parallel, are set inside the simulation project.

Technical assumption

In order to evaluate the available hydrogen technology and its potential for use in HSAPS, it is important to limit the size range of components to include as technology changes upon size / capacity. In this project a limitation of a few hundred kW is set on the power output for the HSAPS system. We have chosen to limit the power generation side to 300 kW. The size / capacity of the other hydrogen technology components are of course dependent of the renewable energy sources and the electricity and heat load given for a specific application. However, in order to be able to assess the status for the different hydrogen technologies approximate capacity ranges has to be set. 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.

The components used in the models are briefly described in Table 4.

TABLE 4.

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

Economic assumptions

In the economic assessment for each of the modelled cases, investment costs, O&M-costs and fuel costs are included. The data have been collected by use of questionnaires to industry in Europe and the USA in the period 2001 to 2003. 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 5 lists the economic assumption for each component.

TABLE 5.

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		Lifetime	O&M
Component	From	To	Unit	A	B	yrs	% of investment
WECS	15	200	kW	0	1400	30	1.5
Micro-hydro	15	35	kW	0	2400	20	1.5
PV	0	inf	kW	0	6750	30	0.0
Electrolyser	2	120	Nm^3/h	0	8150	20	2.0
H_2-storage unit	5	10000	Nm^3	0	38	20	0.5
Fuel cell	5	50	kW	0	3000	10	2.5
Battery	0	1000	kWh	0	100	7	1.0
DEGS	5	50	kW	6000	140	6	2.0

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 6.

TABLE 6.

Present and future costs for the hydrogen energy system components

Hydrogen technology component	Type	Unit	2003-5	Long-term (2020)
Electrolyser	Alkaline (>30 bar outlet pressure)	€ / Nm^3/ h	8150	4075*
Fuel Cell	PEM	€ / kW	3000	300♣
H2-storage unit	Compressed gas (low-pressure < 100 bar)	€ / Nm^3	38	25♠

* 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, pricate communication

Modelling results

A comparison of the cost of energy for the conventional SAPS and HSAPS in the short (2003-2005) and long term (2020) for all simulated cases is given in Figure 16. No change in time of the price of conventional technology is intro-

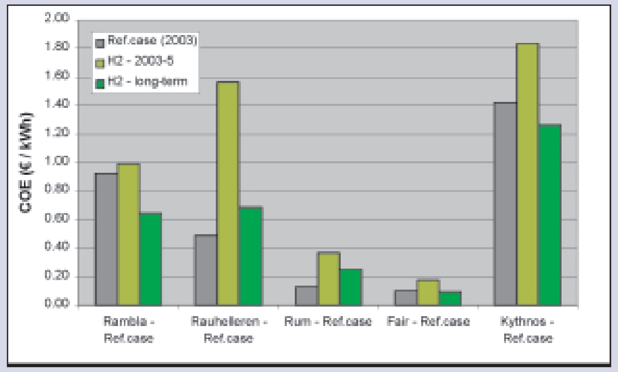

Figure 16. Comparison of the cost of energy (COE) for the conventional SAPS and HSAPS in 2003-5 and in the long-term for the 5 simulated cases.

Figure 17. Rauhelleren Tourist Cabin, Norway, Hardanger National Park.

duced 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.

MAIN CONCLUSIONS

At present an HSAPS system has a much higher cost per generated energy than conventional SAPS. The main cost driver is the H2 storage for systems with poor matching of RE energy and load. For systems with better matching the electrolyser becomes the main cost driver.

Storage of energy as hydrogen is expensive and the predicted reductions in price of compressed gas storage still render storage the main critical cost parameter in the future.

Good renewable energy resources are needed in order to make HSAPS competitive in the future. It is equally important that RE energy sources match the load in a best possible way. This means that one should evaluate the installation of more than one RE sources, since this can reduce the need for long-term storage.

For the example cases the PV-based systems with load in phase with solar insulation give HSAPS with potential competitive advantages based on costs in the long-term. This is a result of the reduced need for really long-term storage. Load management is essential to HSAPS as well as SAPS.

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