Hydrogen Demonstration Project Evaluations

FINAL REPORT

for

IEA – International Energy Agency
HIA – Hydrogen Implementing Agreement

Task 18: Integrated Systems Evaluation
Subtask B: Demonstration Project Evaluations

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Abbreviations & Symbols

AB₃  LaNi₅-based metal hydride alloy
AIST-ETRI  National Institute of Advanced Industrial Science and Technology, Energy Technology Research Institute (Japan)
APCI  Air Products and Chemicals, Inc. (USA)
ASME  American Society for Mechanical Engineers
BOP  Balance of Plant
CaFCP  California Fuel Cell Partnership
CHP  Combined Heat and Power
CIEMAT  Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (Spain)
CIS  CuInSe₂ (type of PV solar cell)
CNG  Compressed Natural Gas
COE  Cost of Energy
ECTOS  Ecological City Transport System
EES  Engineering Equation Solver
ELY  Electrolyzer
EMS  Energy Management System
FC  Fuel Cell
FIRST  Fuel cell Innovative Remote System for Telecom
GenOpt  Generic Optimization tool (USA)
H₂  Hydrogen
HARI  Hydrogen and Renewables Integrated
HAZOP  Hazard and Operability Study
HOMER  Optimization model for distributed power (USA)
HSAPS  Hydrogen Stand-Alone Power Systems
HYDROGEMS  Hydrogen Energy Models library (Norway)
ICP-CSIC  Instituto de Catálisis y Petroleoquímica, Consejo Superior de Investigaciones Científicas (Spain)
IFE  Institute for Energy Technology (Norway)
INTA  Instituto Nacional de Técnica Aeroespacial (Spain)
IU  Current - voltage (e.g. IU-curves fuel cells)
kwₚ  Peak power in kilowatts
LPG  Liquefied Petroleum Gas
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MH</td>
<td>Metal Hydride</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration (USA)</td>
</tr>
<tr>
<td>NCEP</td>
<td>National Centers for Environmental Prediction (USA)</td>
</tr>
<tr>
<td>NRC-IFC</td>
<td>National Research Council - Institute for Fuel Cell Innovation (Canada)</td>
</tr>
<tr>
<td>O&amp;M</td>
<td>Operation &amp; Maintenance</td>
</tr>
<tr>
<td>PCT</td>
<td>Pressure - Concentration - Temperature (e.g. PCT-curves metal hydrides)</td>
</tr>
<tr>
<td>PEM</td>
<td>Proton Exchange Membrane</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic</td>
</tr>
<tr>
<td>PVHSAPS</td>
<td>Photovoltaic Hydrogen Stand-Alone Power System</td>
</tr>
<tr>
<td>PSS</td>
<td>Pacific Spirit Station</td>
</tr>
<tr>
<td>RE</td>
<td>Renewable Energy</td>
</tr>
<tr>
<td>RE/H₂</td>
<td>Renewable Energy Hydrogen</td>
</tr>
<tr>
<td>SOC</td>
<td>State of Charge (e.g. for batteries or hydrogen storages)</td>
</tr>
<tr>
<td>TRNOPT</td>
<td>GenOpt plug-in and interface for TRNSYS</td>
</tr>
<tr>
<td>TRNSED</td>
<td>Menu-based TRNSYS simulation environment</td>
</tr>
<tr>
<td>TRNSYS</td>
<td>A Transient System Simulation program</td>
</tr>
<tr>
<td>URFC</td>
<td>Unitized Reversible Fuel Cells</td>
</tr>
<tr>
<td>V AC</td>
<td>Voltage for Alternating Current</td>
</tr>
<tr>
<td>V DC</td>
<td>Voltage for Direct Current</td>
</tr>
<tr>
<td>VFCVP</td>
<td>Vancouver Fuel Cell Vehicle Program</td>
</tr>
<tr>
<td>WE</td>
<td>Water electrolyzer</td>
</tr>
</tbody>
</table>
1 Executive Summary


The overall objective of Annex 18 is to provide information on progress in the hydrogen economy. Thirteen countries were formal members of Phase 1 of Annex 18. These were: Canada, Denmark, France, Iceland, Italy, Japan, Netherlands, Norway, Spain, Sweden, United Kingdom, United States, and the European Commission. In addition, a Swiss representative sponsored directly by the Hydrogen Implementing Agreement participated in the Annex.

There were two subtask groups in Phase 1. Subtask A, Information Base Development has built a series of information or data bases, including national documents, national capabilities, a compilation of demonstration projects, a hydrogen resources technology cost and performance data set, and a set of links to other appropriate sites.

Subtask B “Demonstration Project Evaluations” has the overall goal to study and analyze hydrogen demonstration projects currently deployed within the participating countries. In Subtask B modeling tools are used to help guide, assess, and evaluate the overall design and performance of a variety of integrated hydrogen demonstration projects. This report describes the work performed within Subtask B, Phase 1.

The general method adopted has been to gather technical and operational data from various stationary hydrogen energy demonstration systems within the Annex 18 membership. Custom made, specific system simulators based on the data collected and a set of known hydrogen energy system models were developed. The data collected from each of these systems was used to verify and improve the models and assumptions used in the modeling tools, and/or to investigate alternative designs.

The scope of work in Phase 1 of Subtask B included:
- Five (5) demonstrations were modeled and analyzed in detail.
- Three (3) demonstrations were analyzed in less detail.
- Eight (8) demonstrations were discussed in case studies; three (3) of these were also looked at in more detail.

The portfolio of systems included in the modeling and evaluation in Phase 1 of Annex 18 are listed below in Table 1.
Table 1 Portfolio of Hydrogen Demonstration Projects evaluated in Subtask B.

<table>
<thead>
<tr>
<th>#</th>
<th>Description</th>
<th>Fuel type/source</th>
<th>Analysis</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Hydrogen energy station</td>
<td>NG-reforming for ICE- vehicles and stationary FC</td>
<td>General performance</td>
<td>Las Vegas, USA</td>
</tr>
<tr>
<td>2</td>
<td>Stand-alone power system</td>
<td>PV/H₂-system (with MH)</td>
<td>Detailed solar simulation</td>
<td>Madrid, Spain</td>
</tr>
<tr>
<td>3</td>
<td>Grid-connected load-leveling hydrogen energy system</td>
<td>Integrated MH-system</td>
<td>Storage thermal modeling and optimization</td>
<td>Atsugo, Japan</td>
</tr>
<tr>
<td>4</td>
<td>Hydrogen refueling station / city buses</td>
<td>H₂/NG-mixes</td>
<td>Bus performance optimization; station expansion sizing</td>
<td>Malmö, Sweden</td>
</tr>
<tr>
<td>5</td>
<td>Hydrogen refueling station</td>
<td>Electrolyzer system</td>
<td>Electrolyzer model; system optimization</td>
<td>Reykjavik, Iceland</td>
</tr>
<tr>
<td>6</td>
<td>Hydrogen refueling station</td>
<td>H₂-storage/compression</td>
<td>Compression / dispensing model and optimization</td>
<td>Vancouver, Canada</td>
</tr>
<tr>
<td>7</td>
<td>Hydrogen and renewable integrated system</td>
<td>RE/H₂ mini-grid system</td>
<td>System efficiency and dispatch optimization</td>
<td>Leicestershire, UK</td>
</tr>
<tr>
<td>8</td>
<td>Domestic solar/hydrogen system</td>
<td>PV/H₂-system (with MH)</td>
<td>Dispatch control model</td>
<td>Brunate, Italy</td>
</tr>
</tbody>
</table>

The five demonstration systems modeled in detail include an electrolyzer-based hydrogen refueling station in Reykjavik, Iceland; a refueling station/city bus project in Malmö, Sweden; an integrated electrolyzer/metal hydride/fuel cell system in Takasago, Japan; a hydrogen and renewable integration (HARI) project running in Leicestershire, UK; a PV/hydrogen telecom system in Madrid, Spain, called the Fuel cell Innovative Remote System for Telecom (FIRST) project. The three demonstrations analyzed in less detail were a natural gas reformer-based hydrogen energy station in Las Vegas, USA; a passenger vehicle hydrogen refueling station in Vancouver, Canada; a domestic solar/hydrogen system in Brunate, Italy. More detailed analysis of the demonstration hydrogen systems in Vancouver and Brunate were left for Subtask B Phase 2.

A number of case studies were also carried out as part of Annex 18. These case studies are more descriptive of the project background, parties involved, and overall experiences, but less detailed in performance analysis. These documents make instructive reading and can be found on both the Annex 18 website (www.port-h2.com/IEA-Annex-18/) and the Hydrogen Implementing Agreement website (www.ieahia.org). Seven case studies were completed by Dr. Thomas Schucan during the course of Phase 1. Some of these are companions to the more detailed analyses mentioned previously. The case studies completed during Phase 1 of Annex 18 are listed in Table 2 below.
Table 2  Case Studies published during Phase 1 of Annex 18.

<table>
<thead>
<tr>
<th>#</th>
<th>Case Study</th>
<th>Country</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>“California Fuel Cell Partnership (CaFCP)”</td>
<td>USA</td>
</tr>
<tr>
<td>2</td>
<td>“Compressed Hydrogen Infrastructure Project (CH2IP)”</td>
<td>Canada</td>
</tr>
<tr>
<td>3</td>
<td>“Fuel Cell Innovative Remote System for Telecom (FIRST)”</td>
<td>Spain</td>
</tr>
<tr>
<td>4</td>
<td>“Ecological City Transport System (ECTOS)”</td>
<td>Iceland</td>
</tr>
<tr>
<td>5</td>
<td>“Hydrogen and Renewables Integration (HARI) Project”</td>
<td>UK</td>
</tr>
<tr>
<td>6</td>
<td>“PEM Fuel Cells in Real Conditions” (EPACOp)</td>
<td>France</td>
</tr>
<tr>
<td>7</td>
<td>“H2 Truck”</td>
<td>Denmark</td>
</tr>
</tbody>
</table>

Comparisons between data and models show that the hydrogen system simulators developed are capable of evaluating systems with respect to design and operation (e.g. energy efficiency and system availability). The work to date has been successful, but more work is needed. Specifically, more exact data on hydrogen compressor work is required to adequately model compressor performance. Alternative hydrogen compression and storage systems for refueling stations can result in improved performance.

Detailed analyses show how important it is to properly understand the heat exchange mechanisms and characteristics (kinetics) of metal hydrides before designing fully integrated metal hydride systems. It is also very important that the operation of hydrogen system control is adequately modeled, if a realistic picture of hydrogen systems operation is to be attained from simulations. In the case of HARI, for example, the heart of the dispatch control is a Zebra battery system. This component has been somewhat difficult to model due to a lack of manufacturer’s data.

Analysis of three hydrogen fueling stations (Reykjavik, Malmö, and Vancouver) show that there are four (4) key system design parameters for electrolyzer-based hydrogen refueling stations: (1) Electrolyzer operating pressure, (2) Compressor operating pressures, (3) Hydrogen storage capacity (dependent on pressure and volume), and (4) Hydrogen demand (pressures and flow rates). The operating pressures in commercially available electrolyzers are typically in the range 1-15 bar, depending on the technology selected (non-commercial 30 bar electrolyzers are under development). Alternative designs and operational schemes for existing electrolyzer-based hydrogen stations were investigated. Analysis shows that there exist optimal hydrogen compression and storage system configurations. A multistage compressor and storage system, with a flexible design and several operational advantages, is recommended.

The following general conclusions can be made from Annex 18 Subtask B:

**System Evaluations:**
- Proper validation of data, detailed modeling and system analysis is a tedious process; a minimum of two person-years should be allowed for each detailed evaluation.

**Data Monitoring:**
- More extensive monitoring of systems is required; project developers must be made aware of how important this is and should be given a list of parameters to measure.
- It is difficult to measure hydrogen flow in compressors, as these are dependent on temperature and pressure.
• Energy measurements and validated models for hydrogen compressors are needed for benchmarking of the technology.

Modeling Tools:
• Optimal design and operation of integrated hydrogen systems can only be found on a case-by-case basis; validated modeling tools are needed.
• The development of generic hydrogen energy models (e.g. HYDROGEMS) should be continued, and made available for several system simulation platforms (e.g., TRNSYS, EES, MATLAB).

System Design:
• Thermally coupled electrolyzer/metal hydride/fuel cell systems for stationary applications can have high overall energy system efficiency, up to 45-50%.
• Demonstration systems are often over-sized; this is particularly true for electrolyzer-based hydrogen fueling stations.
• The efficiency of electrolyzer systems can be improved by 10-15% with new and more innovative balance of plants and operational schemes.

Controls Systems:
• Control system models need to be handcrafted for each specific system configuration
• Demonstrations system can provide a test-bed for testing of control algorithms, as in the FIRST and HARI projects.

Cost-Benefit Analyses:
• Hydrogen component cost-functions (e.g., data bases at Sandia National Laboratory, USA and IFE, Norway) should be updated.
• Cost functions including replacements due to limited life, commissioning, O&M costs etc. should be coupled to technical models.

It is envisioned that the methods and procedures for the technical evaluations described in Annex 18 Subtask B can be applied to different types of hydrogen projects and for projects at different stages of development, from laboratory demonstrators through to fully operational installations.

Phase 2 of Annex 18 was approved by the Hydrogen Implementing Agreement Executive Committee in November 2006. The Task will operate from January 2007 through December 2009. Subtask B will continue with the ongoing objective to model and analyze integrated hydrogen demonstration systems. The first activity in Phase 2 will be modeling of the Italian hydrogen house, with a focus on control strategies and system performance. Another priority of Phase 2 is gathering data on compressor operations to improve compressor modeling. Yet another priority will be including a reformer-based project in the portfolio. Finally, the group will work to continue comparisons between similar systems for the purpose of trend analysis and lessons learned.

Specific Recommended future work in Phase 2 of Annex 18:
• Perform three (3) new detailed technical evaluations (fill voids in renewable energy and natural gas system matrix).
• Develop new models for CHP-systems, hydrogen compressors, and generic controllers.
• Set up simulations so that they are more suitable for techno-economic system optimization.
2 Introduction


The overall objective of Annex 18 is to provide information on progress in the hydrogen economy. Thirteen countries were formal members of Phase 1 of Annex 18. (See sidebar.) There were two subtask groups in Phase 1. Subtask A, Information Base Development has built a series of information or data bases, including national documents, national capabilities, and a compilation of demonstration projects.

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The general method adopted has been to gather technical and operational data from various stationary hydrogen energy demonstration systems within the Annex 18 membership. Custom made, specific system simulators based on the data collected and a set of known hydrogen energy system models were developed. The data collected from each of these systems was used to verify and improve the models and assumptions used in the modeling tools, and/or to investigate alternative designs.

The scope of work in Phase 1 of Subtask B included:
- Five (5) demonstrations were modeled and analyzed in detail.
- Three (3) demonstrations were analyzed in less detail.
- Four (4) demonstrations were discussed in case studies.

The five (5) detailed technical simulations carried out in Subtask B Phase 1:
1. An electrolyzer-based hydrogen bus refueling station in Reykjavik, Iceland.
2. An integrated electrolyzer/metal hydride/fuel cell building load-leveling system in Takasago, Japan
3. An integrated renewable energy hydrogen system located on a domestic farm in Leicestershire, UK, the hydrogen and renewables integration (HARI) project
4. A solar photovoltaic/hydrogen fuel cell-powered telecommunication system in Madrid, Spain, the Fuel cell Innovative Remote System for Telecom (FIRST) project
5. A refueling station / city bus project in Malmö, Sweden, in which buses were fueled by a mixture of hydrogen and natural gas
The three (3) less detailed evaluations carried out:
1. A natural gas reformer-based hydrogen energy station in Las Vegas, USA
2. A passenger vehicle hydrogen refueling station in Vancouver, Canada
3. A domestic solar/hydrogen system in Brunate, Italy

More detailed analysis of the demonstration hydrogen systems in Vancouver and Brunate were left for Subtask B Phase 2. General descriptions of all the systems can be found in References [1]-[8].

Proper validation of data, detailed modeling, and system analysis is a tedious process; hence, a minimum of 1-2 person years was allowed on each detailed demonstration evaluation. Comparisons between data and models show that the hydrogen system simulators developed are capable of evaluating systems with respect to design and operation (e.g. energy efficiency and system availability).

The case studies are more descriptive of the project background, parties involved, and overall experiences, but less detailed in performance analysis. These documents make instructive reading and can be found on both the Annex 18 website (www.port-h2.com/IEA-Annex-18/) and the Hydrogen Implementing Agreement website (www.ieahia.org).

In this report, Chapters 3 provides an overview of the evaluation methodology and Chapter 4 introduces the hydrogen modeling tools used in this work to date. The bulk of the report is divided into Parts I and II. Part I describes the hydrogen-based power systems which have been evaluated, and Part II describes the hydrogen refueling stations which have been evaluated. In each case, the Annex 18 group visited the facility, and that visit is also described briefly. Chapter 14 provides conclusions and recommendations derived from this work for future efforts on how to apply the tools available to similar hydrogen energy systems and refueling stations.
3 General System Evaluation Methodology

The main categories of demonstrations systems considered for evaluation within Annex 18 are summarized in Table 3 (number of identified systems in each category indicated in the last two columns), while Table 4 gives an overview of the demonstration projects and evaluated (in more or less detail) in Annex 18.

Table 3 Categories of system for evaluation in Annex 18 Subtask B

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>RE-based</th>
<th>NG-based</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Grid-connected power systems</td>
<td>none</td>
<td>few</td>
</tr>
<tr>
<td>2</td>
<td>Refueling stations</td>
<td>many</td>
<td>many</td>
</tr>
<tr>
<td>3</td>
<td>Combinations of 1 &amp; 2</td>
<td>none</td>
<td>few</td>
</tr>
<tr>
<td>4</td>
<td>Stand-alone power systems (SAPS)</td>
<td>many</td>
<td>none</td>
</tr>
</tbody>
</table>

Legend: RE = Renewable Energy, NG = Natural Gas

Table 4 Annex 18 demonstration projects evaluated in Subtask B (listed in chronological order).

<table>
<thead>
<tr>
<th>#</th>
<th>Description</th>
<th>Comments</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Hydrogen energy station</td>
<td>NG-reforming for ICE-vehicles and stationary FC</td>
<td>Las Vegas, USA</td>
</tr>
<tr>
<td>2</td>
<td>Stand-alone power system (FIRST)</td>
<td>PV/H2-system (with MH)</td>
<td>Madrid, Spain</td>
</tr>
<tr>
<td>3</td>
<td>Grid-connected load-leveling hydrogen energy system</td>
<td>Integrated MH-system</td>
<td>Atsugo, Japan</td>
</tr>
<tr>
<td>4</td>
<td>Hydrogen refueling station</td>
<td>H2/NG-mixes</td>
<td>Malmö, Sweden</td>
</tr>
<tr>
<td>5</td>
<td>Hydrogen refueling station</td>
<td>Electrolyzer system</td>
<td>Reykjavik, Iceland</td>
</tr>
<tr>
<td>6</td>
<td>Hydrogen refueling station</td>
<td>H2-storage/compression</td>
<td>Vancouver, Canada</td>
</tr>
<tr>
<td>7</td>
<td>Hydrogen and renewable integrated system (HARI)</td>
<td>RE/H2 mini-grid system</td>
<td>Leicestershire, UK</td>
</tr>
<tr>
<td>8</td>
<td>Domestic solar/hydrogen system</td>
<td>PV/H2-system (with MH)</td>
<td>Brunate, Italy</td>
</tr>
</tbody>
</table>

The level of detail in the system evaluations performed in Annex 18 Subtask B varied from system to system. The system simulations performed can be placed in three categories:
1. Detailed component-level simulations (e.g., Takasago system, Japan)
2. Detailed systems simulations (e.g., ECTOS-project, Iceland; FIRST-project, Madrid)
3. Strategic energy systems simulations (e.g., HARI-project, UK).

The selection process for technical evaluations in Annex 18 Subtask B was based on the following three principles:
1. **First come, first serve:** Those who already have an installation, and are ready to provide info about their project will be evaluated first.

2. **Quality, before quantity:** At least one detailed evaluation of a project will be performed each year.

3. **Technical tour of the project:** A visit to the demonstration projects that are considered for evaluation will be made, preferably in the same year as the evaluation.

The main technical (and quantifiable) parameters considered in the evaluation of the demonstration systems are:

1. Energy efficiency (%)
2. System availability (hours)
3. Emissions (grams)
4. Costs ($) 

All of these parameters are dependent on the system design and operation, which makes the evaluation complex. Hence, in order to limit the scope of the technical simulations the focus has been to evaluate each system only with respect to (1) Energy efficiency and (2) System availability.

The general evaluation methodology adopted can be summarized as follows:

1. Obtain system design and operational data from existing demonstration plants.
2. Verify models based on data obtained from physical installations.
3. Model physical system based on common system simulation and modeling tools.
4. Identify and improve shortcomings in data and models.
5. Evaluate overall system performance using calibrated models.
6. Recommend alternative designs and/or operation for selected demonstrations.
## 4 Hydrogen Energy Models & Simulation Tools

The modeling and system analysis performed within Annex 18 is based on the HYDROGEMS-library, which is a collection of hydrogen energy models suitable for simulation of integrated hydrogen energy systems, particularly renewable energy systems (www.hydrogems.no). The models have been developed by the Norwegian Institute for Energy Technology (IFE) since 1995 and were made publicly available for TRNSYS 15 in 2002 [9]. The models were officially integrated within TRNSYS 16 in 2005 (http://sel.me.wisc.edu/trnsys). During 2002-2005 about 175 HYDROGEMS users from 56 organizations in 20 countries were registered.

The basic theory behind the HYDROGEMS component models are thermodynamics, electrochemistry, and applied physics (e.g., electrical, mechanical and heat and mass transfer engineering). As a result the models are fairly physical and generic, but in order to make the models suitable for energy system simulations some simplifications have been made. This is done by using empirical relationships for current-voltage characteristics (\(IU\)-curves) for solar cells or electrochemical cells (e.g., fuel cells, batteries, electrolyzers), power curves for wind turbines, efficiency curves for electronic equipment (e.g. AC/DC-inverters), etc. Typical system model parameters are: (i) Component sizes (e.g. cell areas), (ii) System sizes (e.g., number of cells in series or parallel per module), and (iii) Limits (e.g., min/max of voltages, currents, temperatures etc.). Typical forcing functions required for renewable energy system simulations are wind speed (m/s), solar radiation (W/m²), current (A) or power (W) demand, while typical variables calculated by the models are temperature (°C), pressure (bar), current (A), voltage (V), and flow rate (Nm³/h).

The empirical parts of the models are designed so that it is possible to find default parameters and/or calibrate coefficients based on data found in literature (e.g. product data sheets, papers and articles). It is a challenge to calibrate model parameters and coefficients. Hence, access to actual data from the hydrogen demonstration systems being modeled [10] (i.e., from Annex 18) is essential to ensure the validity of the models. This data source is also useful in updating the parameters of the models in a rapidly changing technical field.

The HYDROGEMS-library consists of the following component models:
- Wind energy conversion systems (WECS)
- Photovoltaic systems (PV)
- Water electrolysis (advanced alkaline, adaptable to PEM)
- Fuel cells (PEM and alkaline)
- Hydrogen gas storage
- Metal hydride hydrogen storage (added during Annex 18)
- Hydrogen compressor
- Secondary batteries (lead-acid)
- Power conditioning equipment
- Diesel engine generator systems (multi-fuels, including hydrogen)

The source code for all of these models, except the metal hydride model and alkaline fuel cell model, are available for registered TRNSYS16 users. IFE has also developed a duplicate HYDROGEMS library for EES (www.fchart.com) based on the exact same source code as that developed for TRNSYS, but these are only made available through collaborative projects.
5 Reference Hydrogen Energy System Laboratory

The modeling and simulation tools used in Annex 18 Subtask B (discussed in more detail in Chapter 5) are closely linked to IFE’s modeling activities, which in turn are closely linked to a small-scale hydrogen system laboratory at IFE for the testing of autonomous renewable energy hydrogen (RE/H₂) systems (Figure 1).

This RE/H₂-system laboratory, sometimes also referred to as the hydrogen stand-alone power (HSAPS) laboratory, currently consists of a 5 kW wind turbine, 5 kW PV-system emulator, 1.5 kW PEM (proton exchange membrane) electrolyzer, 14 Nm³ metal hydride hydrogen storage system, and a 1.2 kW PEM fuel cell. The laboratory system is designed for testing of individual components, subsystems, and complete power system operation. For example, in 2006, a new water-cooled PEM fuel cell unit was integrated with a water cooled/heated metal hydride storage unit designed and built at IFE [11-13].

In Annex 18 it was important to incorporate practical experience in the detailed modeling and system evaluations. Thus it was convenient to use the IFE laboratory set-up as a reference hydrogen energy system, particularly in those instances were experimental data on individual components from the demonstration projects was lacking. Such data could be related to the characteristics of individual components (electrolyzer, metal hydride, or fuel cell), design of electrical and thermal balance of plants (BOPs), and/or basic algorithms for control of RE/H₂-systems.

![Figure 1 Schematic of the small-scale renewable energy hydrogen system laboratory at IFE in Norway, with photos of the new components integrated into the system in 2006.](image)
PART I – HYDROGEN ENERGY SYSTEMS
6 Photovoltaic Hydrogen Stand-Alone Power System in Madrid (Spain)

6.1 Background

The objective with the project “Fuel cell Innovative Remote System for Telecom (FIRST)” was to build, test, and showcase small-scale photovoltaic hydrogen (PV/H₂) stand-alone power system concept suitable for telecommunication applications.

The partners in the FIRST-project (Mar 2000 - Feb 2004, 50% funding by EC) were:

- INTA (Spain): Project coordinator and hosting of Showcase 1
- Air Liquide (France): Hydrogen and air supply systems and controls
- Fraunhofer ISE (Germany): Electrolyzer and energy management system
- CIEMAT (Spain): Hosting and operation of Showcase 2
- ICP-CSIC (Spain): Metal hydride storage and purification system
- NUVERA Fuel Cells (Italy): PEM fuel cell stacks
- Würth Elektronik (Germany): PV-generator and MPP charge controller

Two experimental systems built and tested in Madrid during the 4-year project period, showcase 1 and 2. The designs for these two showcases were based on an average energy consumption of 3.6 kWh/day and an average power demand of 150 W, which are typical design parameters for telecom power supply units.

The first showcase system demonstrated was a PV/battery/H₂-storage/fuel cell hybrid system, where the main purpose with the fuel cell was to provide back-up power in case of an energy shortage in the batteries. The hydrogen was delivered to the system from an external source (transport to the site). The main objective with this demonstration was to test the reliability and maintenance service required for this system configuration, compared to conventional back-up systems for remote area telecom applications, typically diesel engine generators.

The second showcase system demonstrated was a fully autonomous PV/H₂-system consisting of a PEM water electrolyzer, a metal hydride hydrogen storage system, and an air/hydrogen PEM fuel cell (Figure 2 and Figure 3). The main objective with Showcase 2 was to demonstrate the production of hydrogen via water electrolysis during sunny periods with excess solar energy, storage of hydrogen in a long-term energy storage system, and generation of electricity on demand via a fuel cell. In order to fulfill the strict telecommunication requirements in terms of size and reliability it was necessary to further develop the actual state-of-the-art the main components: electrolyzer, metal hydride storage, fuel cell, and energy management system.

A fairly comprehensive case study of the FIRST-project was performed as part of Annex 18 [14]. Unfortunately, only a limited amount of data from actual system operation was made available from the FIRST-project to Annex 18. It was therefore impossible to calibrate component model (HYDROGEMS) parameters and perform detailed system analyses (via simulations). However, a PV/H₂ stand-alone power system (PVHSAPS) simulator originally developed by IFE was further developed in Annex 18 based on data from the FIRST-project. This PVHSAPS-simulator is suitable for detailed evaluations of Showcase 2 system configurations, and is described in some detail below.
Figure 2 Photos of the FIRST-project Showcase 2 hybrid PV/H₂ stand-alone power system configuration demonstrated at CIEMAT in Madrid. Left: Electrolyzer, fuel cell, and energy management system (EMS). Right: PV-panels and water supply.

Figure 3 Schematic of the FIRST-project Showcase 2 hybrid PV/H₂ stand-alone power system configuration demonstrated in Madrid.
6.2 Site Visit at INTA in Madrid on 7 September 2004

On 7 September 2004 the Annex 18 group made a site visit to the Showcase 1 system. The expected tour of Showcase 2 did not take place because of problems with the electrolyzer and the metal hydride storage system. However, the energy management system (which determines the electricity flow from the PV and fuel cell systems) developed in the FIRST-project was viewed in the control room.

6.3 System Description

The basic system design and key specifications for the main components in Showcase 2 PV/H₂-system (Figure 3) was as follows:
- PV-array: 1.5 kW₀, thin-film CIS-type (CuInSe₂), 22 modules
- Water electrolyzer: 1.0 kW, PEM-type, 30 cells, 30 cm² electrode area
- Hydrogen storage: 70 Nm³ H₂, AB₅-type metal hydride, 700 kg
- Fuel cell: 0.3 kW, PEM-type, 48 cells, 50 cm² electrode area
- Battery: 48 V, 400 Ah, lead-acid type
- Electrical load: 133-197 W (146 W average), standard radio equipment

The following auxiliary equipment was required: Water supply and purification system for the electrolyzer, hydrogen purification units for drying (zeolites and activated carbons) and removal of oxygen (Pd catalyst) for the metal hydride, and nitrogen flushing system for the fuel cell. A DC/DC-converter for the fuel cell and an energy management system (EMS) was also required for smooth operation and control of the PV/H₂-system.

6.4 System Design Parameters

The design of a stand-alone PV/H₂ power system known solar radiation and specific electrical load, such as the case for professional telecom application, depends on several parameters.

For a stand-alone PV/H₂ system with a directly coupled electrolyzer (Figure 3), the number of electrolyzer cells in series (i.e., overall electrolyzer stack voltage) needs to correspond to the nominal voltage on the DC-busbar, which in this case was 48 V. The power rating for the fuel cell can be derived from the maximum electrical load requirement (including a safety factor).

Hence, based on the above assumptions the following parameters can be changed in order to obtain an optimal system design:
- Nominal PV-generator power (W)
- PV-generator mounting (slope and orientation)
- Nominal battery capacity (Ah)
- Electrolyzer area per cell (cm²) and resulting the nominal power (W)
- Hydrogen storage capacity (Nm³)
- Operation and control parameters (e.g. on/off-switching of electrolyzer/fuel cell)
6.5 Operation and Control Parameters

A sophisticated energy management system (EMS) was developed for the Showcase 2 system in the FIRST-project. Table 5 shows the system variables logged and used by the EMS, and indicates the complexity of the control systems required for PV/H₂-systems. The practical control system developed in the FIRST-project confirms the results from other studies [13,15,16], which also have demonstrated the importance of having sophisticated control strategies for on/off-switching of the electrolyzer and fuel cell in stand-alone PV/H₂ power systems.

Table 5 Operation and control variables logged and used by the energy management system (EMS) in the FIRST-project PV/H₂ Showcase 2.

<table>
<thead>
<tr>
<th>No.</th>
<th>Operation variable</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Solar irradiation</td>
<td>W/m²</td>
</tr>
<tr>
<td>2</td>
<td>Power of PV-generator</td>
<td>W</td>
</tr>
<tr>
<td>3</td>
<td>Voltage of PV-generator</td>
<td>V</td>
</tr>
<tr>
<td>4</td>
<td>Current of PV-generator</td>
<td>A</td>
</tr>
<tr>
<td>5</td>
<td>Temperature of EMS</td>
<td>ºC</td>
</tr>
<tr>
<td>6</td>
<td>Voltage of batteries</td>
<td>V</td>
</tr>
<tr>
<td>7</td>
<td>Current of batteries</td>
<td>A</td>
</tr>
<tr>
<td>8</td>
<td>State of charge of batteries</td>
<td>%</td>
</tr>
<tr>
<td>9</td>
<td>Temperature of batteries</td>
<td>ºC</td>
</tr>
<tr>
<td>10</td>
<td>Power of batteries</td>
<td>W</td>
</tr>
<tr>
<td>11</td>
<td>Voltage of fuel cell</td>
<td>V</td>
</tr>
<tr>
<td>12</td>
<td>Current of fuel cell</td>
<td>A</td>
</tr>
<tr>
<td>13</td>
<td>Temperature of fuel cell</td>
<td>ºC</td>
</tr>
<tr>
<td>14</td>
<td>Power of fuel cell</td>
<td>V</td>
</tr>
<tr>
<td>15</td>
<td>Single cell voltages of fuel cell stack</td>
<td>V/cell</td>
</tr>
<tr>
<td>16</td>
<td>Temperature of hydrogen storage system</td>
<td>ºC</td>
</tr>
<tr>
<td>17</td>
<td>Pressure of hydrogen storage system</td>
<td>bar</td>
</tr>
<tr>
<td>18</td>
<td>Current of electrolyzer</td>
<td>A</td>
</tr>
<tr>
<td>19</td>
<td>Voltage of the electrolyzer</td>
<td>V</td>
</tr>
<tr>
<td>20</td>
<td>Temperature of electrolyzer</td>
<td>ºC</td>
</tr>
<tr>
<td>21</td>
<td>Room temperature</td>
<td>ºC</td>
</tr>
<tr>
<td>22</td>
<td>Room hydrogen alarm</td>
<td>%</td>
</tr>
</tbody>
</table>
6.6 Identification of System Evaluation Parameters

The data on the operation and control variables logged by the EMS-unit (Table 5) can be used to generate a set of general (quantitative) evaluation parameters with respect to the system's actual performance, namely:

- System and sub-system efficiencies (%)
- Renewable energy utilization factor (%)
- Availability of main component units (%)
- Start-up times for main component units (minutes)
- Overall and average run-times for main component units (hours)

The system design parameters (listed in Section 6.4) and the operation performance parameters listed above all affect the cost of the system. Hence, it is important that both system design and operation parameters both are included in a techno-economic system optimization.

The most logical objective function to optimize is the cost of energy (COE) for the overall system (€/kWh), including all investment costs and operation and maintenance costs. A formal method on how to calculate the COE for hydrogen stand-alone power systems (HSAPS) has been developed in other studies [17].

6.7 PV/Hydrogen Stand-Alone Power System (PVHSAPS) Simulator

IFE has over the years developed a PV/H₂ stand-alone power system (PVHSAPS) simulator based on a set of hydrogen energy models (HYDROGEMS) and two energy system simulation platforms, EES and TRNSED (part of TRNSYS). This PVHSAPS-simulator was further developed in Annex 18 Subtask B.

The original idea in Annex 18 Subtask B of was to:
1. Calibrate all of the individual component models (HYDROGEMS) based on operational data from the Showcase 2 system
2. Update the TRNSYS weather data to include a number of Spanish locations.
3. Configure the PVHSAPS-simulator so that it resembled the actual design of the Showcase 2 system
4. Perform detailed system simulations and evaluate the design and operation the Showcase 2 system.

During the course of Annex 18 it was not possible to obtain operational data suitable to calibrate the models, and some simplifications on the modeling needed to done. Fortunately, at IFE in Norway there exists (and still exists) a PV/H₂ laboratory system [12] with a PEM-electrolyzer very similar (same manufacturer) to the one installed in Madrid, that has been fully characterized.

The characteristics (IU-curve) of this PEM-electrolyzer, along with the characteristics of a generic PEM fuel cell model was used instead of actual data. No model for the metal hydride storage was included in the PVHSAPS-simulator, as this was left for subsequent Annex 18 modeling exercises (Chapter 7). A view of the PVHSAPS-simulator main diagram window (in EES) is shown in Figure 4.
The PVHSAPS-simulator was re-configured to resemble the PV/H₂ Showcase 2 system. One part of this work was to add long-term solar radiation data (and temperature data) for a few Spanish locations into the existing weather database, which currently consists of more than 400 locations around the world (USA, Canada, Australia, Europe, and Norway).

The PVHSAPS-simulator is designed so that long-term data on solar radiation, temperature, and humidity be easily accessed and viewed in a “Weather Generator”. The weather generator’s main diagram window in EES is shown in Figure 5, while an example of the monthly average solar radiation for three different locations (from Madrid in the south to Tromsø in the north) is shown in Figure 6.

The main purpose with the weather generator EES-program shown in Figure 5 is to link the PVHSAPS-simulator, which is a freestanding EES-program, to a self-executable TRNSYS weather simulator with a TRNSED front-end, as shown in Figure 7. The advantage with the TRNSED-program is that can, based on standard TRNSYS component models, generate hourly time series for solar radiation, temperature, and humidity. Figure 8 shows the generated hourly solar radiation profile used in the PV/H₂-system simulations described in this chapter.
Figure 5  PVHSAPS-simulator’s weather generator main diagram window (EES).

Figure 6  Monthly average total solar radiation on a horizontal surface as a function of latitude (long-term meteorological data).
The PVHSAPS-simulator has several levels for setting system parameters and component coefficients, in addition to the superficial level shown in Figure 4. At the second level down it is possible to set the main system design parameters, either via a separate diagram window, directly in an equation editor window, or in lookup tables.
Further characterization and specification of individual components is normally done at a third level, in other individual EES-programs linked (normally via hyperlinks) to the main PVHSAPS-simulator. Figure 9 shows the EES diagram window for the PV-array simulator, which allows the user to investigate the current-voltage ($I_U$) characteristics and power curves for PV-modules in the database. Figure 10 shows the $I_U$-curves and power curves for the CIS-based PV-array installed in the FIRST-project Showcase 1 system, and used in the simulations described in this chapter.

The advantage with the combined use of the PVHSAPS-simulator (Figure 4) and PV-generator model (Figure 9) is that this makes it possible to get a complete overview of the most suitable electrical configurations. This is particularly important in systems where the electrolyzer is directly coupled (without a DC/DC-converter) to the PV-generator via a DC-busbar. (Note: The state of charge of the battery will determine the voltage on the busbar in such a setup).

The PEM fuel cell program shown in Figure 11 is another example of a component model program that is interrelated (this time not directly linked) to the PVHSAPS-simulator. The PEM fuel cell program can be used to investigate fuel cell stacks with suitable designs for the overall system, and can be used to map out technicalities related to different electrical topologies (voltage and current), hydrogen processes (flow rates and pressures), or thermal management systems (temperatures and flow rates).

Figure 12 shows the $I_U$-curve and power curve for a PEM fuel cell with a stack design similar to the one installed in the FIRST-project Showcase 2 system. It should be noted here that this characteristic is based on the coefficients of a generic PEM fuel cell model, and has not been calibrated with actual data. Nevertheless, the modeled PEMFC-curves should be in fairly good agreement with the actual PEMFC-characteristics.

In the simulations described in this chapter it was assumed that the fuel cell and electrolyzer warm up quickly, and reach their nominal operating temperature (70-80'C) within an hour. Hence, no effort was made on modeling the thermal management system. This simplification can only be justified for simulations with large time steps, such as the case here where the time step was one hour, and/or where the aim is to get an overview of the main electrical energy flows.

In studies where there is more focus on the thermal integration of components (e.g. between fuel cell and metal hydride), or specific focus on improving the overall system efficiency, it is necessary to make the $I_U$-curves for the electrolyzer and fuel cell temperature dependent and to use the detailed thermal models available in HYDROGEMS. This is explored further in separate simulations studies in Chapter 7.
Figure 9  PV-array simulator main diagram window (EES).

Figure 10  PV-generator current and power curves as a function of voltage, solar radiation on the surface (G_T), and average PV-module temperature (T_PV).
Figure 11  PEM fuel cell simulator main diagram window (EES).

Figure 12  PEM fuel cell stack voltage and power as function of stack current.
6.8 Typical PVHSAPS Simulation Results (Simulation Study 1)

The PVHSAPS-simulator described above can be used to evaluate alternative system designs and control strategies for a given solar radiation and load profile. The tools can also be used to evaluate the performance of a given design and control strategy for alternative locations with other solar radiation profiles.

In the FIRST-project there were performed detailed techno-economical analyses (internal reports, details not enclosed in this report), which demonstrated that there exists an economical optimal system design. One of the most economically optimal system designs is shown in Figure 3.

In a PV/H₂ stand-alone power system size of the electrolyzer is mainly dependent on the need to produce hydrogen during summer, while the size of the hydrogen storage is mainly dependent on the amount of hydrogen required during the winter. In addition, the size of the hydrogen storage will also be affected by the size of the battery, as this affects the operation of the fuel cell. A large battery will enable the system to operate for longer periods without operation of the fuel cell, thus reducing the need for stored hydrogen.

Figure 13 summarizes a typical simulation of a PV/H₂ stand-alone power system based on the FIRST Showcase 2 system configuration described above (Figure 3). The main difference between this simulation and the real system is that a DC/DC-converter is included on the electrolyzer side (i.e., not directly coupled). However, this should not affect the main energy flows significantly.

It should also be noted that only the main electrical current flows and hydrogen mass balances was modeled, and that no power losses from the auxiliary equipment was included. As a result the simulated system appears to perform better than the actual system. This is clearly seen in the development of the hydrogen storage level in (Figure 13, top plot), which shows net hydrogen production over the year (increase from 50% to 80%). In the actual system there will be auxiliary loads that will consume power that partially will have to be covered by the fuel cell, and; hence, will consume more hydrogen that what is shown.

One of the nice features of the PVHSAPS-simulator is the possibility to investigate various electrical configurations and actual (current and/or voltage based) control strategies for the electrolyzer, fuel cell, and battery. However, in order to be able to perform such detailed analyses it is necessary to use component models that are fully calibrated with respect to their electrical performance. A typical check on the battery voltage and current quickly reveals how well the electrolyzer and fuel cell design and controls match with the battery (Figure 13, middle plot).

In a detailed technical analysis it is important to be able to get an overview of the key system performance statistics, such as individual component run times (i.e., number of operating hours) and number of ON/OFF-switches (Figure 13, bottom plot), as this affects the system life time and efficiency, and consequently the overall system costs.

Finally, if component cost functions (investment and O&M), such as those developed in the HSAPS-project [17], are integrated into the PVHSAPS-simulator, it is quite straightforward to find cost-effective system designs.
Figure 13  Typical PVHSAPS simulation results (Modeling Case Study 1).
Top plot: Electrolyzer and fuel cell power and H₂ storage state of charge.
Middle plot: Battery voltage and current charging/discharging.
Bottom plot: Number of electrolyzer and fuel cell operating hours.
6.9 Conclusions

The FIRST-project Showcase 2 system, a PV/H₂ stand-alone power system (PVHSAPS) for a telecommunication application, has been built, tested, and operated, as part of an EU-project.

A PVHSAPS-simulator was further developed as part of Annex 18 Subtask B. The basic system design (main component sizes), solar radiation data, and load profile was derived from the FIRST-project. The hydrogen energy models (HYDROGEMS) used in the simulator were not calibrated due to lack of operational data, but these models have been verified in other studies and should be sufficiently accurate to demonstrate the simulation tools developed.

A PV/H₂-system based on the Showcase 2 system configuration can at first glance appear to be a fairly simple type of integrated hydrogen energy system. However, at a second glance this concept has several technological challenges, as shown in the separate Annex 18 case study [14], as well as several challenges on system design and operation, as illustrated via the PVHSAPS-simulator described in this report. In summary, the following general conclusions can be made:

- The design of integrated PV/H₂-systems depends heavily on the location (solar radiation) and the power demand (load profile) for the given application. The FIRST-project demonstrated that by carefully specifying the power demand (in this case a telecom power unit), it is possible to optimize the design for a given location.
- The operational performance of integrated PV/H₂-systems is less dependent on the choice of location and power demand, as long as these are not outside the specifications for hydrogen technology (e.g., freezing, access to clean water), and more dependent on the how the electrolyzer and fuel cell operate together with the battery. The PVHSAPS-simulation tools developed in Annex 18 Subtask B can be used to perform detailed analyses of various electrical configurations and control strategies.
7 Hydrogen Energy Storage System in Atsugi (Japan)

7.1 Background

The storage of electricity in the form of hydrogen can only be justified if hydrogen storage systems with high overall energy efficiencies can be developed. The need for electrical storage varies with the application, from seasonal energy storage in remote area photovoltaic (PV) power systems (e.g., telecom applications), to daily energy storage (night time to day time) in grid-connected systems (e.g. high cost markets, such as Japan).

The hydrogen energy storage system concept described in this report discusses how an integrated electrolyzer/metal hydride/fuel cell system can produce hydrogen at night time (excess grid electricity), store this hydrogen in a metal hydride system, and finally convert the hydrogen back to electricity in a fuel cell during daytime.

The original concept of using a metal hydride hydrogen storage system for load leveling of grid-electricity was developed by Dr. Yoshiyuki Kozawa (Gifu University, Japan), who in 2000 initiated modeling and experimental work on such systems [18]. This work eventually lead to a detailed metal hydride system model, and the design, building, and testing of a laboratory system at the Research and Development Center of Takasago Thermal Engineering Co., Ltd., in Atsugi, Kanagawa, Japan [3], hereafter simply referred to as the Takasago system or plant (Figure 14 and Figure 15). The Energy Technology Research Institute (ETRI) at the National Institute of Advanced Industrial Science and Technology (AIST) in Tsukuba has been the main research partner in the development of the overall Takasago system concept.

The main objective with the Takasago demonstration system is to develop highly efficient, compact, and cost-efficient hydrogen energy storage systems based on water electrolysis, metal hydrides, and fuel cells. The R&D targets are as follows:

1. Improve the system efficiency using advanced thermal engineering (short-term targets)
2. Develop new hydrogen energy technology, unitized regenerative fuel cells (URFC) in particular, leading to more compact and cost-efficient systems (long-term targets).

The objective with the work performed within Annex 18 Subtask B was to study the design and overall performance of the Takasago demonstration system, with focus on the short-term R&D targets. Thus, special focus was made on modeling of the metal hydride system and the thermal integration of this with the electrolyzer and fuel cell. The Takasago project partners had already developed and verified a detailed two-dimensional metal hydride model [3]. However, this model was too detailed for readily available energy system simulation tools (e.g., TRNSYS or EES).

In Annex 18 it was therefore decided to use actual data from the Takasago system to develop and verify a hydrogen energy storage system simulator (Figure 20) based on a new and simpler zero-dimensional metal hydride model. This model was developed as part of a PhD-study performed at IFE [19], but had only been partially verified [20]. The main benefit with a zero-dimensional metal hydride model is that it readily can be used with existing hydrogen energy models (HYDROGEMS) and made suitable for simulation of renewable energy systems (e.g. PV/H2-systems). Nevertheless, the focus of the modeling and system analysis presented in this report was on the Takasago integrated energy system concept.
Figure 14  Photos of the integrated hydrogen energy storage demonstration system located at Takasago Thermal Engineering Co. Ltd in Atsugi, Kanagawa, Japan.

Figure 15  Schematic of the Takasago system, including water electrolyzer (WE), metal hydride (MH) storage units, fuel cell (FC), and heating and cooling systems.
7.2 Site visit to the Takasago Plant in Atsugi on 31 March 2005

On 31 March 2005 participants from Annex 18 visited the Research and Development Center at Takasago Thermal Engineering Co., Ltd., Atsugi, Kanagawa, Japan (Figure 14). The company’s engineers presented an overview of the following two demonstration systems: (1) the unitized regenerative fuel cell (URFC) system and (2) the hydrogen energy storage system (hydrogen integrated system) (Figure 15). Translators were kindly made available throughout the tour and discussions, making the question and answer session particularly valuable.

7.3 System Description

The main hydrogen energy components in the Takasago demonstration system are two electrolyzer units (only the small 3 Nm³/h (20 kW) unit evaluated here), three hydrogen storage units consisting of AB₅-type metal hydrides (total weight of 210 kg and hydrogen storage capacity of 100 Nm³), and a single PEM-fuel cell (5 kW). The balance of plant (BOP) consists mainly of a hydrogen dehumidifier (after the electrolyzer) and humidifier (before the fuel cell), and cooling units (exhaust heat recovery) for the metal hydride and fuel cell. A schematic of the overall system is provided in Figure 15.

The general objective with the Takasago plant is to demonstrate electricity load leveling by using hydrogen energy technology, which is economically feasible in Japan because of the low cost of electricity at night-time, as it is about 50% of the daytime cost [18]. This means that the hydrogen energy system needs to be capable of running the following two processes:

1. Conversion of excess electricity during night-time to hydrogen by electrolysis and adsorption in metal hydrides
2. Conversion of hydrogen back to electricity during day-time by desorption of hydrogen in metal hydride storage and fuel cell operation.

The main challenge with the Takasago system concept is to increase the overall energy efficiency of the system. Detailed studies show that improving the BOP (cooling, dehumidification, and humidification systems), for the electrolyzer; metal hydride fuel cell, an overall energy efficiency of 45.8% can be reached in the near future (short-term target) [3]. This is illustrated in the energy flow (%) diagram in Figure 16.

7.4 System Design and Operation Parameters

The three key system design parameters for an integrated hydrogen system based on water electrolysis, metal hydrides, and fuel cells are as follows [3]:

1. Heat exchange mechanism
2. Electrolyzer pressure
3. Metal hydride characteristics (PCT-curves and H₂ adsorption/desorption reaction rates)

All of these three parameters must be taken into consideration when designing a system that maximizes the utilization of the MH-storage capacity, as illustrated in Figure 17. High overall efficiency can only be achieved in a fully integrated system, including carefully designed regenerative heating/cooling systems. It should be noted here that the MH-system system described in Figure 17 represents a fairly unique design, as the desorption process (release of hydrogen) takes place at a fairly low temperature (ca. 10°C). The reason for this is the availability of cold heat (ca. 10°C) for roof-mounted cooling systems in Japan.
Figure 16  Energy flow diagram for the Takasago system concept, showing possible improvements on water electrolyzer (WE), metal hydride (MH), fuel cell (FC), and heat recovery systems, and a realistic target for the overall energy efficiency (45.8%) [3].

Figure 17  Pressure-Temperature diagram for constant hydrogen composition in a metal hydride alloy (M/H=0.5), showing critical MH-system design parameters [3].
The operation and control of integrated electrolyzer/metal hydride/fuel cell systems is heavily dependent on the determination of the state of charge (i.e., hydrogen concentration) of the metal hydride. This is particularly true for systems that are thermally fully integrated, such as the Takasago plant, and if the electrolyzer is coupled to a stochastic renewable energy source, such as a PV-generator.

In order to optimize the system operation and controls it is first necessary to determine the pressure-composition isotherms (PCT-curves) and the kinetics of the hydrogen adsorption and desorption reaction rates of the metal hydride used in the actual system. A schematic of the mass and heat transfer processes and hydrogen reactions taking place in a metal hydride tank is shown in Figure 18.

A detailed two-dimensional engineering model for a metal hydride tank, including absorption and desorption reaction flows ($X_a$ and $X_d$ and heat generation and absorption ($Q_a$ and $Q_d$), was developed by the Takasago project partners. The main objective with this modeling tool was to optimize the design, specifically to maximize the utilization of the metal hydride storage capacity. This depends heavily on the hydrogen reaction flows and temperatures in the metal hydride. For example, if the metal hydride cools down too fast it will not be possible to charge it 100%.

A comparison between simulated values and experimental data from the Takasago plant is provided in Figure 19 [4], and shows that the detailed metal hydride model gives an accurate predication of the pressure, temperature, and flow rates, both for absorption and desorption mode. This demonstrates the need to model both the heat transfer processes and the kinetics of the hydrogen reactions, which also must be taken into account in a simpler metal hydride model suitable for renewable energy hydrogen system simulations.
7.5 System Evaluation Methodology

The evaluation of the design and operation of the Takasago system was has been done on several different levels (by several different research groups). In summary, the following two-step methodology has been applied:

1. **Japanese project team (Takasago Thermal Engineering Co., Ltd.):**
   Testing and verifying the performance on the actual installations in place at the Takasago plant (Figure 15) and on developing and on verifying a two-dimensional metal hydride model (Figure 18).

2. **IEA Annex 18 Subtask B project team (IFE and AIST):** Establishing a zero-dimensional metal hydride model suitable for renewable energy hydrogen system modeling based on HYDROGEMS and EES (Figure 20) and verifying this by running simulations based on the Takasago system design.

This means that the approach in Annex 18 was to try to use as much as possible of the existing experimental data from AIST and Takasago (Japan) and combine this with existing models developed at IFE (Norway). The characteristics of the main individual components (electrolyzer, metal hydride, and fuel cell) installed in the Takasago plant were compared to the same components installed in IFE’s small-scale RE/H₂ system laboratory (Chapter 5). The experimental data collected on the PEM electrolyzer and PEM fuel cell IU-curves for and the metal hydride PCT-curves at the Takasago plant was comparable to that collected at the

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Figure 19 Experimental data versus results from simulations with two-dimensional metal hydride model.
IFE system laboratory. Thus, rather than spending a lot of time calibrating the models based on data from the Takasago plant, it was decided to run the Takasago system simulations using hydrogen component model parameters already calibrated in the IFE system laboratory.

As a result the work within Annex 18 could focus more on developing a hydrogen energy storage system simulator (Figure 20), compare the performance of this simulator to actual system performance data from the Takasago plant, and on studying important thermal system integration issues related to the metal hydride system.

### 7.6 Hydrogen Energy Storage System Simulator

The main diagram window for the metal hydride based hydrogen energy system simulator developed within Annex 18 is shown in Figure 20. The basic models and structure for this simulator was based on the PVHSAPS-simulator described above laboratory, and actual data from the operation the Takasago plant.

![Hydrogen energy storage system simulator main diagram window](image)

*Figure 20 Hydrogen energy storage system simulator main diagram window (EES).*
7.7 Metal Hydride System Modeling

In order to make a metal hydride model suitable for thermal energy system simulations it was necessary to develop a fairly physical model that reflects both material and system specific properties, without introducing an excessive number of component model parameters. Thus, a new and simple zero dimensional metal hydride model suitable for hydrogen storage system simulations was developed. This model takes into consideration both material specific properties (pressure concentration isotherms, or $PCT$-curves, and kinetics of hydrogen reactions), as well as more general characteristics of the metal hydride system (heat and mass transfer). The basic metal hydride storage unit simulated in this study was based on an AB5 type metal hydride powder. (Actual MH-systems normally contain several MH-units; in this case there were three MH-units). The main features of the zero dimensional metal hydride model developed can be summarized by the following general function:

$$f_{\text{MH-model}} = f(\text{inputs} : \text{outputs}) = f(m_{\text{MH}}, m_{\text{H}_2}, p_{\text{H}_2}, T_{\text{cw,in}}, m_{\text{cw}}, p_{\text{MH,eq}}, C_{\text{H/MH}}, T_{\text{MH}}, T_{\text{cw,out}})$$ (1)

where

- $m_{\text{MH}}$ = mass of metal hydride powder (kg)
- $m_{\text{H}_2}$ = hydrogen mass flow rate (from electrolyzer or to fuel cell) (kg/s)
- $p_{\text{H}_2}$ = hydrogen gas pressure inside metal hydride storage (bar)
- $T_{\text{cw}}$ = cooling water temperature (inlet or outlet) (°C)
- $m_{\text{cw}}$ = cooling water (i.e., heating water) flow rate (kg/s)
- $p_{\text{MH,eq}}$ = equilibrium pressure of metal hydride (bar)
- $C_{\text{H/MH}}$ = hydrogen concentration in metal hydride (mol H/mol MH)
- $T_{\text{MH}}$ = temperature of metal hydride (K)

The $PCT$-curves for the AB5 alloy used in the simulations of this study were based on measurements at four different temperatures performed in a dedicated experimental setup at IFE [21]. Values for the equilibrium pressures ($p_{\text{MH,eq}}$) in the zero dimensional metal hydride model were then linearly interpolated from tables generated by a more detailed (and experimentally verified) $PCT$-model developed by Lototsky [22]. A semi-empirical kinetic expression developed by Førde et al. [20] was used in the modeling of the reaction rates between the gas and solid for the selected AB5 alloy. The heat and mass transfer properties of the modeled metal hydride reactor were scaled up from a small IFE-laboratory test reactor containing 2.3 kg of metal hydride powder and a brush type heat exchanger. A more detailed description of the heat and mass transfer properties and transient behavior of the reference reactor will be published in the near future [19].
7.8 Characterization of Metal Hydride

The system parameters and coefficients for the models used in the hydrogen energy system simulations described below (in Modeling Case Study 2) were based on *IU*-curves for the PEM-electrolyzer and PEM fuel cell and *PCT*-curves for the metal hydride based on experimental data from IFE. However, these *IU*-curves and *PCT*-curves could relatively easily have been updated with the data provided described below (for completeness).

The measured *PCT*-curves for the metal hydride installed at the Takasago plant is shown in Figure 21. The accuracy of the *PCT*-curves and the detailed metal hydride model developed by the Takasago team is best illustrated by a typical 13-hour hydrogen metal hydride discharge period (fuel cell operation) (Figure 22) [4].

![Figure 21 PCT-curves (pressure composition temperature) for the AB5-type metal hydride installed in the Takasago plant. Top: Absorption. Bottom: Desorption.](image)
The system parameters and coefficients for the models used in the Annex 18 hydrogen energy simulator were based on measured $I_U$-curves for the PEM-electrolyzer and PEM fuel cell and the pressure composition temperature characteristics ($PCT$-curves) of the metal hydride. The accuracy of the $PCT$-curves and the detailed metal hydride model developed by the Takasago team is best illustrated by comparing actual measured values to simulated values for a typical 13-hour hydrogen metal hydride discharge period (fuel cell operation) (Figure 22) [4].

![Figure 22](image)

*Figure 22  Comparison of simulated values based on a detailed two-dimensional metal hydride model and actual experimental data from the Takasago plant, for a typical 13-hour hydrogen discharge period (fuel cell operation) [4].*

The results from a 24-hour simulation based on the zero-dimensional metal hydride model are shown in Figure 23, and demonstrate that it is possible to simulate the overall system performance using empirical $PCT$-curves, and semi-empirical expressions hydrogen reaction kinetics (adsorption and desorption), and generalized thermal equations. Hence, the hydrogen storage simulator can be used to estimate the hydrogen state of charge and gas pressure of a metal hydrides exposed to various dynamic charging/discharging regimes.

![Figure 23](image)

*Figure 23  Calculated metal hydride system state of charge and pressures for a 9 hour charging and 13-hour discharging period using the Annex 18 hydrogen energy system simulator.*
7.9 Application of the Model (Simulation Study 2)

This chapter describes the modeling and simulation of a thermally coupled electrolyzer/metal hydride/fuel cell system performed at IFE based on the hydrogen energy storage simulator described above. A slight variation in the Takasago simulated system configuration was made, as shown in Figure 24. The basic idea with this system is to buffer heat generated by the electrolyzer and fuel cell in two separate water tanks (denoted T1 and T2, respectively).

![Figure 24 Schematic of the simulated electrolyzer/metal hydride/fuel cell system.](image)

The size of the electrolyzer and fuel cell water tanks, found through simulations, was 100 and 1200 liters, respectively. Furthermore, the thermal management of the system was divided into two water loops:

- **Water loop 1 (to/from T1):** High temperature heat transfer between electrolyzer and water tank 1 (e.g., hot tap water at ca. 333K).

- **Water loop 2 (to/from T2):** Low temperature heat transfer between fuel cell, metal hydride, and water tank 2 (e.g., space heating at ca. 323K).

The water flow in water loop 2 can take several directions, as illustrated in Figure 24. For example, during start up of the fuel cell, it is possible to bypass water tank 2 and the metal hydride. Once the fuel cell has reached its operating temperature and produces excess heat, it is possible to optimize the thermal management by regulating the cooling water flow rate through the metal hydride (0-100%) before it goes into water tank 2.

The assumed daily profile for the power flow to/from the simulated system (Figure 24) is shown in Figure 25. This load profile was generated by AIST on the basis of the actual energy consumption (measured data) for a typical Japanese hotel measured [23]. As seen from Figure 25, the electrolyzer operates at a constant power of 11.5 kW for 9 hours during nighttime, before the fuel cell starts up after 10 hours and operates for the next 14 hours at an average power of 2.9 kW (3.7 kW peak power).
In the simulations described below it was assumed that all of the excess thermal energy produced by the fuel cell and metal hydride, minus the heat losses from these components to the surroundings, could be stored in the two water tanks and the metal hydride storage unit. The flow rate of the cooling water from the fuel cell to water loop 2 (fuel cell water loop) is calculated by the following equation:

$$\dot{m}_{cw,FC} = \frac{Q_{cool,FC}}{C_{p,cw} \cdot \Delta T_{FC}}$$

where $Q_{cool,FC}$ is the amount of heat removed from the fuel cell, $C_{p,cw}$ is the heat capacity of cooling water, and $\Delta T_{FC}$ is the temperature difference between the inlet and outlet of the fuel cooling water. In this study $\Delta T = 5$ K was assumed, which was in accordance to the specification of the actual water-cooled PEM fuel cell installed in the RE/H$_2$-system laboratory at IFE. Two different control strategies on how to regulate the water flow in the fuel cell loop were investigated in the system simulations described below:

- **Control Strategy A – No regulation of water flow to the metal hydride:** All of the fuel cell cooling water was first circulated through the metal hydride storage system and afterwards into water tank 2

- **Control Strategy B – Regulation of water flow to the metal hydride:** Fuel cell cooling water was circulated through the metal hydride storage system only if the metal hydride pressure was below a set point; a control pressure of 2 bar was used in this case study.

The temperatures and transient thermal behavior for the electrolyzer, metal hydride, fuel cell, and water tanks for the two different control strategies are shown in the two plots in Figure 26. In control strategy A (Figure 26, top plot) the temperature in the metal hydride increases from ambient temperature (300 K) to 315 K over the 9-hour hydrogen charging period (at constant hydrogen production in electrolyzer, $\dot{m}_{H2,ELY} = 48$ Nl/ min). The excess heat from the electrolyzer is used to heat up water tank 1, and the temperature increases from 300 K to 355 K (at constant electrolyzer cooling water flow rate, $\dot{m}_{cw,ELY} = 15$ kg/min). The heat
generated in the metal hydride during the hydrogen charging period (exothermic reaction) is transferred to water tank 2 (at a constant metal hydride cooling water flow rate, \( \dot{m}_{cw,MH} = 2 \text{ kg/min} \)), and the temperature increases to about 330 K over the same 9-hour time period. A comparison between control strategy A and B (Figure 26, top and bottom plots) confirms that the transient thermal behavior over the first 9-hour hydrogen charging period is independent of the control strategy. This is because there is no difference in the water regulation in water loop 1 (electrolyzer water loop).

After 9 hours, the fuel cell starts up and idles for one hour (at constant power, \( P_{FC} = 100 \text{ W} \)). The hydrogen discharged from the metal hydride during this hour results in (due to endothermic reactions) both a temperature reduction (Figure 26) and a pressure reduction (Figure 27) in the metal hydride. The reduction in metal hydride temperature and pressure during this idling period depends on the control strategy. After 10 hours the fuel cell starts meeting the electrical load (Figure 24), and continues to do so for the next 14 hours (at average fuel cell power, \( P_{avg,FC} = 2.9 \text{ kWel} \)). No water is circulated through the metal hydride or water tank 2 before the fuel cell has reached a minimum operating temperature of 328 K.

In control strategy A (Figure 26, top plot) the temperatures in the metal hydride storage unit and water tank 2 begin to rise after about 45 minutes. After another 2 hours the metal hydride has reached a steady state temperature of 326 K. The temperature in water tank 2 continues to rise throughout the fuel cell operation period, and ends up at 323 K. In control strategy B (Figure 26, bottom plot) no water circulates through the metal hydride before a set point pressure is reached, which in this case was 2 bar (Figure 27, bottom plot). As a result, the metal hydride temperature continues to decrease until it reaches 287 K, which happens after 17.5 hours. In control strategy B, the temperature in water tank 2 increases continuously (similarly to control strategy A), and ends up at 325 K (Figure 26, bottom plot).

Different sizes on the two water tanks were investigated in this study. The simulations showed that in order to reach a high temperature of 328 K it is necessary to install a fairly small 100 liters water tank on the electrolyzer side (water tank 1). If a higher temperature is required, the size of water tank 1 must be reduced even further.

The objective with the fuel cell water loop (water loop 2) is to regulate the thermally coupled fuel cell and metal hydride system in the most energy efficient fashion. To illustrate this point, it was assumed that all of the fuel cell heat (minus losses to the surroundings) was regenerated in water loop 2, and that no auxiliary cooling was allowed. The simulations showed that water tank 2 must be very large, around 1200 liters, in order be able to absorb all of the excess heat from the fuel cell, and at the same time maintain a temperature lower than the nominal operating fuel cell temperature.

To fully understand the behavior of a thermally coupled electrolyzer/metal hydride/fuel cell system it useful to study the transient behavior of the hydrogen pressure and concentration in the metal hydride, as well as the flow rates in the fuel cell water loop (water loop 1). This behavior is illustrated in Figure 27. For both control strategies it can be observed that the hydrogen concentration in the metal hydride increases continuously as long as the electrolyzer operates and produces hydrogen, reaches its peak at 5.1 H/MH (mol H per mol metal atoms), and decreases continuously as long as the fuel cell operates.
It should be noted that the hydrogen gas pressure inside the metal hydride storage unit ($p_{H2}$) is almost equal to the equilibrium pressure of the metal hydride ($p_{MH,eq}$), due to relatively fast kinetics in the given operating temperature range. However, since the hydrogen pressure is strongly dependent on temperature, the evolution in pressure ($p_{H2}$) will depend significantly on the selected control strategy.

The development of the hydrogen gas pressure (i.e., metal hydride equilibrium pressure) is best illustrated by comparing the curves in the top and bottom plots of Figure 27. In control strategy A (Figure 27, top plot), water starts to circulate through the metal hydride already after 11 hours, and the hydrogen pressure increases continuously as long as the temperature increases. After a while the temperature stabilizes and the pressure decreases due to a decrease in the hydrogen concentration in the metal hydride.
In control strategy B (Figure 27, bottom plot), no water circulates through the metal hydride hydrogen storage unit before about 18 hours has passed. At this time a small part of the total water flow from the fuel cell ($\dot{m}_{cw,FC}$) is directed to the metal hydride ($\dot{m}_{cw,MH}$), while the rest (majority of heat) is directed to water tank 1 ($\dot{m}_{cw,T1}$). The small water flow rate ($\dot{m}_{cw,MH} < 1$ kg/min), leads to a slight increase in the metal hydride temperature, which in turn ensures a stable hydrogen gas pressure ($p_{H2}$) around 2 bar (regulation pressure).

Another alternative control strategy where no water passed through the metal hydride was also simulated. This control strategy (not plots shown here) resulted in a hydrogen gas pressure below 0.2 bar and a temperature below 260 K. This result confirms that thermal integration between the metal hydride and fuel cell is absolutely necessary for the system to function properly. It was found that a small part of the excess heat from the fuel cell can increase the hydrogen gas pressure in the metal hydride, which in turn makes it possible to use more of the stored hydrogen in the fuel cell. This result is in agreement with similar theoretical studies [24].
One of the main objectives with this study was to identify system designs and control strategies that yield high overall energy system efficiency. In order to evaluate the overall energy system efficiency the following simplified expression can be used:

\[ \eta_{\text{system}} = \frac{\text{Energy Output (Electrical + Thermal)}}{\text{Energy Input (Electrical)}} = \frac{E_{\text{FC}} + Q_{T1} + Q_{T2}}{E_{\text{ELY}}} \] (3)

where \( E_{\text{FC}} \) is the electrical energy delivered by the fuel cell (to the grid), \( E_{\text{ELY}} \) is the electrical energy delivered to the electrolyzer (from the grid), \( Q_{T1} \) is the thermal energy recovered from the electrolyzer and stored in water tank 1 and the metal hydride, and \( Q_{T2} \) is the thermal energy recovered from the fuel cell and stored in water tank 2 and the metal hydride. The electrical energy system efficiency is simply derived from Equation (3) by omitting the thermal terms (\( Q_{T1} \) and \( Q_{T2} \)) in the calculations.

The simplified efficiency equation above (Equation (3)) does not take into account the losses associated with auxiliary equipment, such as that associated with the air compressor for the fuel cell, hydrogen drying for the metal hydride, or power conditioning for the conversion to/from the electrical grid. Nevertheless, the efficiencies for a few different designs and control strategies were calculated for the 24-hour period above (Figure 25 - Figure 27).

The results showed that the electrical system efficiency was around 40%, independent of the selected control strategies, while the overall system efficiency was around 75%, also fairly independent of the selected control strategy. This high overall system efficiency assumes that the walls of the water tanks are well insulated, with a thermal conductivity, \( k = 0.05 \, \text{W/mK} \), and that there were no heat losses from the pipes and interconnections.

7.10 Conclusions

Thermally coupled electrolyzer/metal hydride/fuel cell systems for stationary applications can have high overall energy system efficiency. Detailed calculations based on the operation data from the Takasago demonstration system in Atsugi, Japan, show that it is realistic to reach an overall energy efficiency of 45.8% in the near future. The three key system design parameters for an integrated hydrogen system based on water electrolysis, metal hydrides, and fuel cells is: (1) Heat exchange mechanisms, (2) Electrolyzer pressure, and (3) Metal hydride characteristics (\( PCT \)-curves and \( \mathrm{H}_2 \) adsorption/desorption reaction rates). All of these three parameters must be taken into consideration when designing a system that maximizes the utilization of the MH-storage capacity. High overall efficiency can only be achieved in a fully integrated system, including carefully designed regenerative heating/cooling systems.

A system simulation model suitable for parametric studies and optimization of design and controls of such integrated metal hydride hydrogen systems have been developed at IFE as part of Annex 18. System simulations show how the electrolyzer, metal hydride, and fuel cell can be thermally coupled and operated together if sized properly. The simulations also illustrate the importance of a thermal coupling between the metal hydride hydrogen storage and the fuel cell. A control strategy (control strategy B) that regulates the water flow through the metal hydride, and thereby ensures that the hydrogen gas pressure in the storage is sufficiently high, was demonstrated and evaluated.
8 Renewable Energy Hydrogen System in Leicestershire (UK)

8.1 Background

An integrated renewable energy hydrogen system, known as the HARI-project (Hydrogen and Renewables Integration), has been installed at West Beacon Farm, Leicestershire, UK (Figure 28). The system is part of larger scheme initiated by the owner of the house (Tony Marmont) to demonstrate and promote sustainability, with particular emphasis on renewable energy, energy conservation, and energy storage [25].

The original system at West Beacon Farm consists of two 25 kW wind turbines, a 13 kWp PV-array, and two micro-hydroelectric turbines with a combined power output of about 3 kW. In addition, the farm includes the following sustainable energy installations: a 10 kW thermal heat pump, circulating water from a coil at the bottom of an artificial lake to provide central heating in the house, a 15 kW electrical, 38 kW thermal combined heat and power (CHP) unit that currently runs on LPG, an evacuated tube solar thermal collectors for water heating, a conservatory used for passive solar space heating, biomass space heating, a battery powered car and a battery-petrol hybrid car. Furthermore, there is no mains water supply, and the rainwater is collected from the buildings’ roofs for washing, flushing, and even as feedstock for the newly installed water electrolyzer.

The purpose of the HARI-project is to demonstrate and gain experience in the integration of renewable energy hydrogen systems, and to develop software models that could be used for the design of future systems of this type in a range of applications. The main idea behind the project is that learning about such systems on a pilot scale, lessons can also be learned that have relevance to the future deployment of hydrogen and renewable energy schemes and to the wider energy industry, particularly the debate about the nature and viability of a potential ‘hydrogen economy’. From a more practical point of view, the HARI-project includes the design, implementation, and operation of a hydrogen energy storage system, and the integration of this with the existing renewable energy system at West Beacon Farm. A comprehensive Annex 18 case study describes the HARI-project in more detail [7].

The actual hydrogen energy system demonstrated as part of the HARI-project consists of an electrolyzer, a pressurized gas store, and fuel cells (Figure 28 and Figure 29). An alkaline electrolyzer produces hydrogen when there is surplus electrical energy available, typically at times with excess solar (PV) and/or wind energy. The hydrogen is stored in standard pressure vessels, and converted back to electricity via two PEM fuel cells, with two different power ratings. The power produced by the micro-hydro turbine, PV-array, wind turbine, and fuel cell is supplied to domestic and office loads at the site.

The original objective with the Annex 18 Subtask B evaluation of the HARI-project was to examine the technical and economic issues associated with two different electrical configurations (400 V AC versus 600 V DC) applied to a hydrogen energy system supplied by a wide range of renewable energy sources and electrical loads. However, due to the lack of operational data it soon became clear that a less detailed evaluation needed to be performed first. Thus, it was decided to focus the HARI-system evaluation on overall system design (sizing of main components) and control issues, using existing simulations models.
Figure 28 Photos of HARI-project at West Beacon Farm, Leicestershire, UK
(Note: No photo of the high-temperature battery, a key component, is shown)

Figure 29 Schematic of the overall concept for the HARI-project, showing the main hydrogen components installed.
8.2 Site visit and workshop at West Beacon Farm on 11 September 2006

On 11 September 2006 the Annex 18 group visited the HARI-project at West Beacon Farm outside Loughborough, Leicestershire, in the southern part of the UK. A representative from Bryte Energy (Rupert Gammon) who was responsible for the design and performance monitoring of the hydrogen system, hosted an extensive technical tour of the demonstration.

A small workshop with focus on design and control issues was also organized at the near-by conference center of Beacon Energy. The discussions here gave a new understanding of the complexity of integrated renewable energy hydrogen systems. The optimization of the design and operation of the HARI-demonstration is particularly challenging because the system configuration is continuously changing due to the addition of new energy technologies. An advanced high temperature battery serves as the heart of the system, as the operation (e.g. on/off-switching of the fuel cells) is based on a battery state of charge control regime.

In order to be able to perform any kind of detailed technical evaluation, a significant amount of detailed data on the performance of the system components needs to be gathered. This has been done in HARI-project, but due to rebuilding of the data monitoring and control system the latest (and most relevant) operational data was not readily available. Furthermore, no detailed battery performance data was available, neither from the manufacturer, nor from the project itself.

The lack of battery data was one of the main reasons for why it was not possible to perform detailed evaluations of various the electrical system configurations at this stage. Thus, the site visit and local workshop confirmed the conclusions made a few months earlier by the Annex 18 modeling team at IFE, University of Strathclyde, and Sgurr Energy [26].

8.3 System Description

The hydrogen production and storage capacities and power ratings of the main energy components in the HARI-project (Figure 29) is as follows:

- PV-array: \( 13 \text{ kW}_p \)
- Wind turbines: \( 2 \times 25 \text{ kW} = 50 \text{ kW} \)
- Water electrolyzer: 50 kW, 8 Nm\(^3\)/h, 25 bar, alkaline
- Hydrogen storage: 2856 Nm\(^3\), 137 bar
- Fuel cells: 2 kW + 5 kW = 7kW, PEM-type
- Battery: 20 kWh, NiNaCl, 250°C
- CHP: 15 kW\(_{el}\)

Auxiliary equipment for the water electrolyzer was needed for the following processes: water supply and purification; deoxidizing and hydrogen drying; and power conditioning (extensive system). In addition, a number of power converters were required to convert power to/from the 600 V DC busbar. It should also be noted that the 5 kW PEM fuel cell unit also includes a small low-temperature battery to regulate the output power.
8.4 Evaluation Methodology

The evaluation methodology used for the HARI-modeling and system simulations performed Annex 18 Subtask B was to:

1. Use standard renewable energy hydrogen models (HYDROGEMS) and simulation software (TRNSYS).
2. Calibrate model parameters based on the basic HARI-project system design.
3. Find forcing functions for wind speed, solar radiation and power demand
4. Simulate system using existing battery state of charge control regime
5. Suggest improvements on design and control

This approach fit well with the objectives in a MSc study undertaken at University of Strathclyde [19] and the planned energy system modeling activities at Sgurr Energy in the UK, which were to:
- Evaluate TRNSYS/HYDROGEMS ability to simulate stand-alone RE/H₂ power systems
- Compare the operation of the two simulation programs HOMER and TRNSYS
- Establish a methodology to optimize the size and performance of RE/H₂ power systems similar to the HARI-system

8.5 Renewable Energy Hydrogen System Simulators

IFE has since 2001 developed several renewable energy hydrogen (RE/H₂) system simulator packages based on TRNSYS and HYDROGEMS. Some of these simulations programs have been used to further develop and evaluate existing systems, such as the wind/hydrogen demonstration plant at the Utsira Island on the South-West coast of Norway [27]. The RE/H₂ system simulations programs developed have also been used to evaluate alternative system concepts, such as hybrid wind/diesel/hydrogen energy systems concepts for remote islands in the Nordic countries (Iceland, Greenland, and the Faroe Islands) [28].

In the more advanced RE/H₂ system simulators developed at IFE, technical models are directly linked to component cost functions [17]. An example on how this can be done by using EES as the host program for post-simulation analysis (energy statistics and system costing) and TRNSYS/HYDROGEMS as the technical system simulator is shown in Figure 30. It should be noted here that a significant effort was made to streamline the program to simulate very specific hybrid diesel mini-grid system configurations. Specific TRNSYS components for system controls have also been developed. Normally, these control models need to be modified to fit different RE/H₂-system designs, such as the HARI-system.

In Annex 18 it was decided to evaluate the HARI-project using TRNSYS version 16, which includes standard versions of the HYDROGEMS component library. The reason for this was that all of the main components in the HARI-system (wind turbines, PV-arrays, electrolyzer, hydrogen storage, and fuel cells) could be modeled using the standard component library. The only component models that needed to be developed specifically for the HARI-system simulations were a high-temperature battery and a special battery state of charge (SOC) controller. However, a simplified simulation that resembles the HARI-project operation (only from an energy flow point of view) can be made if the battery is omitted and the system is controlled based on the state of charge of the hydrogen storage (instead of the battery SOC). This is exactly what was done in the MSc study mentioned above [19].
8.6 System Simulation Parameters and Input

In general, if the main objective of a renewable energy hydrogen system simulation is to study the overall energy system performance (including high-level control strategies) and to perform techno-economical optimization (technical models coupled with cost functions), it is more important to obtain realistic forcing functions (e.g., solar radiation, wind speed, power demand profiles), rather than modeling the exact performance of each model in great detail (e.g. electrical transients, hydrogen kinetics, heat and mass transport phenomena).

Normally, annual time series simulations with time steps of one hour are sufficient to get a good overview of the performance of a specific system design and control strategy. However, if some of the system inefficiencies resulting from idling and/or on/off-switching of the hydrogen components are to be captured in such a system simulation, there needs to be some level of detail in the modeling of each individual component. This means that the energy efficiency must be calculated, rather than preset as a fixed parameter.

In the TRNSYS-simulations described below (Simulation Study 3), the electrical energy efficiency of the renewable energy and hydrogen components were calculated from empirical current-voltage and/or power curves, as illustrated by the HYDROGEMS-electrolyzer model shown in Figure 31.
Figure 31  Main diagram window (in EES) for an alkaline electrolyzer model (executable developed by IFE for the HARI-project evaluation team). The electrical performance (current, voltage, power, and efficiency) for a given hydrogen production at steady state conditions (constant temperature and pressure) is shown in the ‘View Results’ box.

For simplicity, no detailed modeling of the thermal systems (heating, drying, cooling etc.) was included at this stage. Thus, no parameters describing the thermal system were required. Instead, the main components were in each time step assumed to operate at steady state conditions (nominal pressures and temperatures). For a RE/H₂-system with a large energy storage (i.e., hydrogen tank and/or battery) and relatively few start/stops of the main hydrogen components (i.e., electrolyzer and fuel cell), this modeling approach gives a fairly good approximation.

For a system with a small battery storage capacity and/or frequent on/off-switching of the electrolyzer and fuel cell, great care must be taken in the modeling of the electrical and thermal efficiencies of the main hydrogen components. If the control system is closely interlinked with the battery state of charge, as is the case in the HARI-project, an exact model of the specific battery installed should also be made. Such a detailed model was not developed in Annex 18, and is left for further work for research groups in the UK.

In any case, in order to get a realistic RE/H₂-system simulation it is extremely important to use realistic forcing functions. In the simulation study described below it was necessary to determine the power demand, solar radiation, and wind speed profiles. Power demand data (4 kW day time base load) was obtained from the HARI-project, solar radiation data from the NASA website [29], and wind data from the NCEP website [25] and the HARI-project (6 years with monthly averages). The hourly profiles required for the simulations were synthesized using HOMER (Figure 32).
Figure 32  Tabular values and plots of the forcing functions synthesized in HOMER and used as a basis for the HARI-system simulations (TRNSYS and HOMER). Top: Daily hourly power load profile. Middle: Annual monthly average solar radiation profile. Bottom: Annual monthly average wind speed profile.
8.7 Application of the Model (Simulation Study 3)

The Simulation Study 3 presented here was carried out as part of a MSc study at University of Strathclyde [19]. Several simulations were made in HOMER and TRNSYS to find an optimal system design.

The main objectives (repeated here for convenience) with the simulation study was to:
1. Evaluate TRNSYS/HYDROGEMS ability to simulate stand-alone RE/H₂ power systems
2. Compare the operation of HOMER and TRNSYS.
3. Establish a methodology to optimize the size and performance of the HARI system.

In HOMER it was possible to perform a cost-optimization directly, based on a set of predefined cost functions. The following assumptions and restrictions were made in the HOMER-simulations:
- The design of the wind energy conversion system was fixed (fixed power curves)
- No components could be excluded from the system (minimal size = 1kW).
- The size of the CHP unit was to be minimized in order to favor the use of renewable energy sources (even though this is more expensive).

In TRNSYS it is not straightforward to perform a formal cost-optimization, although this can be done using TRNOPT (based on GenOpt, a generic optimization tool), or simulation tools similar to the ones developed at IFE (Figure 31). Thus, a different type of system optimization was performed in TRNSYS, based on the following objectives:
- Minimize the size and; hence, the cost of the system
- Reduce the use of the CHP unit as much as possible
- Maximize the average SOC of the H₂ storage

Table 6 shows the optimized HARI-system design based on simulations performed using HOMER and TRNSYS. A comparison of these results to the actual HARI-system design shows that, with approximately the same solar (PV) and wind power capacity, it is possible to significantly reduce the size of the electrolyzer and hydrogen storage. This is very advantageous, from an economic point of view. It should also be noted that it is possible to install a much smaller CHP-unit, without increasing the size of the fuel cell significantly. The final design (power rating) of the fuel cell will depend on the battery capacity, and on how these two units are operated together, as discussed in more detail below.

<table>
<thead>
<tr>
<th>Component</th>
<th>HOMER</th>
<th>TRNSYS</th>
<th>HARI-system</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV-array</td>
<td>12 kW submodule</td>
<td>12 kW submodule</td>
<td>13 kW submodule</td>
</tr>
<tr>
<td>Wind turbine</td>
<td>50 kW</td>
<td>50 kW</td>
<td>50 kW</td>
</tr>
<tr>
<td>Water electrolyzer</td>
<td>6 kW</td>
<td>9 kW</td>
<td>50 kW</td>
</tr>
<tr>
<td>Hydrogen storage</td>
<td>511 Nm³</td>
<td>488 Nm³</td>
<td>2856 Nm³</td>
</tr>
<tr>
<td>Fuel cells</td>
<td>10 kW</td>
<td>9 kW</td>
<td>7 kW</td>
</tr>
<tr>
<td>CHP</td>
<td>1 kW/submodule</td>
<td>3 kW/submodule</td>
<td>15 kW/submodule</td>
</tr>
</tbody>
</table>
A more detailed comparison of the results obtained with the HOMER and TRNSYS simulations shows that there is good agreement between the two programs in this type of general energy flow simulations. Here it should be noted that the system control strategies implemented in HOMER is completely different than those in TRNSYS. This means that the main energy components (e.g. CHP, electrolyzer, fuel cell) do not operate in the same way, making it difficult to perform a straight comparison of the two models. However, it is possible to compare the two models by looking at accumulated values, such as the hydrogen storage state of charge and daily energy balance.

The fluctuations of the hydrogen storage state of charge (SOC) over the year are very similar for the two optimal system configurations found in TRNSYS and HOMER (Figure 33). In both cases the following general seasonal pattern for the hydrogen SOC can be observed: high level during the winter and spring periods, a major drop during the summer period (due to low wind resource, see Figure 32), followed by a sharp increase in hydrogen SOC in the fall. This indicates that there is excess power from the renewable energy system during the first part of the year, while the fuel cell must be used extensively during the summer period to compensate for the lack of power available from the renewable energy system. Excess wind energy is available from the fall and last the rest of the year, enabling the electrolyzer to run and re-fill the hydrogen storage.

The energy balance (energy production – energy consumption) in the system also shows some interesting similarities between the two simulation models (Figure 34). The curves follow the same trend and fluctuations, which indicates that there is a similar energy management in HOMER and TRNSYS. A correlation between the energy balances for TRNSYS and HOMER confirms this (Figure 35); the correlation coefficient here was close to unity ($R^2 = 0.98$). The energy balance in HOMER is about 15% higher than in TRNSYS. This is mainly due to the fact that the electrolyzer in HOMER assumes zero power during idling. This is not the case with the HYDROGEMS electrolyzer model in TRNSYS, which assumes a minimum idling power of 25% for this kind of alkaline electrolyzers (in some conventional systems this could be as high as 40-50%).

Based on the above it can be concluded that it is possible to arrive at fairly similar optimal system configurations using HOMER and TRNSYS, even though these are based on very different control strategies. This means that both programs can be used for this kind of general optimization of RE/H$_2$ system designs. From the experience made by the Annex 18 modeling team (IFE and University of Strathclyde), the following assessment can be made of the two programs with respect to RE/H$_2$-system simulations:

**HOMER:**
- Easy to set up and executes fast
- Cost-optimization can be performed directly
- Detailed modeling of individual components or control strategies cannot be performed
- A good tool for screening possible RE/H$_2$-system design configurations

**TRNSYS:**
- Requires more time to setup and executes fast (but not as fast as HOMER)
- Flexible and modular simulation platform (possible to make advanced technical models)
- Not straightforward to perform cost-optimization (but possible with TRNOPT)
- A good tool for investigating RE/H$_2$-system design and controls in detail
Figure 33  Simulated hydrogen storage state of charge (SOC) for the two optimized HARI-system designs using TRNSYS and HOMER.

Figure 34  Daily energy balance (production – consumption) calculated in TRNSYS.

Figure 35  Correlation between energy balances found by HOMER and TRNSYS.
8.8 Battery State of Charge Controls

The TRNSYS simulation setup described above is an excellent starting point for more detailed and refined RE/H₂-system simulations, where the objective is to find both optimal system designs and control strategies. For these kinds of detailed simulations to make sense it is important to use detailed models for the main components (e.g. electrolyzer, fuel cell, and battery) that account for idling powers and other parasitic energy losses. In more advanced simulations it is also necessary to include clever sub-system design and controls (e.g. regenerative heating).

In the HARI-system a special battery state of charge control regime has been implemented (Figure 36). This control system is designed to operate the electrolyzer when the battery has a high battery state of charge (between $ELY_{HIGH}$ and $ELY_{LOW}$) and the fuel cells when the battery state of charge is low (between $FC1_{HIGH}$ and $FC1_{LOW3}$). The on/off-switching of the two fuel cells is quite clever: The smallest fuel cell (2 kW) is started first. If the battery SOC continues to decrease, this fuel cell is switched off (to idling), and the second fuel cell (5 kW) is started and brought online. Finally, if the battery SOC to decreases even further, the first fuel cell (2 kW) is brought back online, together with the second fuel cell (5 kW), enabling the system to deliver maximum fuel cell power (7 kW).

In Annex 18 it was hoped that this interesting control regime could have been studied in detail, using both experimental data and detailed simulation tools. However, in order to test this control algorithm properly a detailed (empirical) model of the special high-temperature battery (NiNaCl, 250°C) needed to be developed first. Since operational data from the HARI-project and battery characteristics from the manufacturer was not available for Annex 18, it was not possible to develop a proper battery model and; hence, it was not possible to study the controller in detail either.

![Figure 36 System control regime implemented in the HARI-system, showing the on/off-switching of fuel cells and electrolyzer as a function of battery state of charge. FC1 = 2 kW fuel cell, FC2 = 5 kW fuel cell 2 (5 kW), and ELY = 34 kW electrolyzer.](image-url)
Nevertheless, a new TRNSYS component model of the HARI-system control actions described above (Figure 37) was developed within Annex 18 (at IFE). A simple energy flow (kWh) battery model was also developed to verify that the control actions were properly programmed into TRNSYS. However, a proper test with a more detailed NiNaCl-battery is left for future work.

In HYDROGEMS there exists a lead-acid battery model that was considered used in the TRNSYS simulations, but since the HARI-system control strategy is based on a battery that allows for really deep battery discharge (Figure 36, $FC1_{LOW3} = 10\%$) this would have resulted in completely meaningless results.

![Flow chart](image)

**Figure 37** Flow chart (only top part shown) for the new battery SOC controller developed for TRNSYS 16, based on the control regime used in the HARI-project.

### 8.9 Conclusions & Recommendations

The following conclusions can be made from the evaluation of the HARI-system concept:

- There is an excellent correlation between the HOMER and TRNSYS RE/H₂-system simulation results.
- General system cost optimization using HOMER or TRNSYS shows that it is possible to reduce the size of some of the key system components, particularly the electrolyzer, hydrogen storage, and CHP-unit.
- There is a difference in system operation observed in HOMER and TRNSYS due to different control strategies.
- An optimal system is only truly optimal if both the system design and control strategy has been optimized.
Based on the above conclusions, the following recommendations can be made:

- RE/H\textsubscript{2} system simulation studies should be continued to be made in TRNSYS
- The new battery state of charge controller developed for simulation of the HARI-system concept should be tested and compared to actual data from the HARI-project
- A detailed NiNaCl should be developed
- Alternative RE/H\textsubscript{2} system configurations (including stand-alone power systems) should be investigated in more detail, with particular focus on the novel electrical configurations.
- A proper cost-benefit model for the HARI-project should be developed in TRNSYS
- A fast, reliable, and generic optimization process using TRNSYS and GenOpt (TRNOpt) should be developed.

The TRNSYS-based RE/H\textsubscript{2}-system modeling work in the UK described in this report is continuing in a Knowledge Transfer Partnership (KTP) involving Sgurr Energy and the University of Strathclyde. The main objective of modeling work carried out in this KTP-project is to develop proper cost-benefit models for RE/H\textsubscript{2}-systems.
9 Domestic Solar/Hydrogen (PV/H₂) System in Brunate Italy

A domestic solar/hydrogen (PV/H₂) system in Brunate, near Como, Italy is under development (Figure 38) [8]. The commissioning and first operation of the PV/H₂-system in Brunate will take place in 2007. Thus, only a brief introduction to the project is provided here in this report. A more complete technical evaluation of the system is left for future work in the Phase 2 of Annex 18.

The key components in the PV/H₂-system in Brunate are: A PV-array (11 kWp), an alkaline water electrolyzer (1 Nm³/h) with a hydrogen compressor (200 bar) built into it, a hydrogen storage (90 Nm³ in gas cylinders and 30 Nm³ in MH-storage), a PEM fuel cell (5 kW), and a battery (48 V, 3000 Ah). The PV-system is connected to the electrolyzer via a separate DC/DC-converter, and to the 48 V system busbar via another DC/DC-converter. The fuel cell and battery are also connected to the DC-busbar (Figure 39).

The load management system controls the flow of the photovoltaic power such that when the electrolyzer is not in operation the power can be transferred from the PV directly to the load. The hydrogen produced by the electrolyzer is controlled by the flow management system.

The control strategy is based on the basis that the metal hydride (MH) storage is the primary storage mechanism and the pressurized tanks secondary, i.e. when hydrogen is produced it is stored first in the MH and second in the tanks. When hydrogen is required by the fuel cell it is transferred first from the MH and second from the tanks. The load, which is a private residence, is managed by the load management system, and is supplied by the 5 kW PEM fuel cell and a 3000 Ah battery, and the PV if the electrolyzer is switched off.

The following evaluation of the PV/H₂-system in Brunate is proposed for Annex 18 Phase 2:
1. Use technical and operational data from the actual PV/H₂-system and calibrate the parameters of a PV/H₂-system simulation model similar to the one developed for the Takasago system evaluation¹ (Figure 20).
2. Use the PV/H₂-system simulation tool to optimize the overall energy management system (i.e., power flow from PV to load, batteries, and electrolyzer).
3. Find optimal methods for hydrogen discharge in the MH-system using excess heat from PEM fuel cell and/or solar domestic hot water (from solar collectors).

An evaluation of the design and controls of this system is already underway in the Annex 18 extension.

¹ Note: It is possible to expand the Takasago hydrogen energy storage system simulator so that it includes a PV-array input, rather than grid-electricity)
Figure 38 Photos of the domestic PV/H₂-system in Brunate, Italy.

Figure 39 Schematic of the PV/H₂-system in Brunate, Italy.
PART II – HYDROGEN FUELING STATIONS
10 Hydrogen Energy Station in Las Vegas (USA)

10.1 Background

The Las Vegas Hydrogen Energy Station Demonstration (Figure 40) took about three years to plan and build. The first phase of the project was from October 2002 to October 2004. The station was designed and built to provide pure hydrogen and 65/35 natural gas/hydrogen blends to city fleet vehicles via gaseous fuel dispensers and electricity to the grid via a Plug Power 50 kW PEM fuel cell stack (Figure 41).

The main partners in this project were Air Products and Chemicals, Inc. (APCI) (project leader), Plug Power, and the City of Las Vegas. The project site is an existing fueling station for alternative fuels including compressed natural gas (CNG), bio-diesel, and ethanol. Hydrogen capabilities have been added through the production and purification of hydrogen from natural gas, the compression and high-pressure storage of that hydrogen, and the use of that hydrogen both in a stationary fuel cell to produce electricity for the city and in a dispensing station where that hydrogen can be introduced into vehicles either in its pure form or in a blend with natural gas.

The site was designed so that the city fleet could benefit from being able to utilize both CNG/hydrogen blends in combustion engines and pure hydrogen in fuel cell vehicles. The site supports the City of Las Vegas’ fleet of vehicles, and Las Vegas employees can dispense the fuels. However, APCI manages the equipment remotely from Sacramento, CA and Allentown, PA via a planar lightweight circuit platform.

10.2 Site visit in Las Vegas on 2 March 2003

On 2 March 2004 the Annex 18 group made a site visit to the Las Vegas Hydrogen Energy Station in order to learn about it and to determine if it is a suitable candidate for further analysis. The meeting was hosted by Mark Wait (Senior Principal Project Engineer) and Dave McCarthy (Commercial Manager) in Air Products and Chemicals and Dan Hyde (Fleet Manager) in City of Las Vegas. There was a very high enthusiasm on the part of The City of Las Vegas to use hydrogen; Dan Hyde cited federal and state laws that call for cleaner fuels, and mentioned that Ford has a hydrogen internal combustion engine.

After the site visit the Subtask B leader and Annex 18 group members from the US tried to convince the project leader (APCI) to provide detailed technical information about the Las Vegas Hydrogen Energy Station. However, because of the contract (or lack of text within the contract) with the US Department of Energy (DOE was one of the main sponsors of the project), APCI did not feel obligated to provide this information and engage in a detailed technical system analysis with Annex 18. Thus, only a brief overview of the installation, with focus on safety issues, and the main lessons learned from the project are summarized in this report.
Figure 40  Photos of the Las Vegas Hydrogen Energy Station.

Figure 41  Schematic of the overall concept for the Las Vegas Hydrogen Station.
10.3 System Description

The hydrogen facility is located on a concrete pad, with most of the equipment (other than the dispensers) behind a fence. Some subsystems are completely enclosed in a confined space. There is a wall behind the facility, and on the other side of that wall are a series of public softball fields. Many of the pieces of equipment have warning signs on them saying that hydrogen is in use. The closed facilities and warnings signs give visitors and people from the outside an impression that hydrogen is dangerous, and that one should keep well away from the premises.

The hydrogen generator consists of a reformer, gas compressor (synthesis gas), and pressure swing adsorption (PSA) purification system, and is enclosed in a confined space. It is monitored for safe access and includes ultraviolet/infrared gas detection that has the capabilities of shutting down the system. (It should be noted that UV/IR detectors sometimes give false positive readings, although this is more likely to happen when exposed to sunlight, which will not happen inside of the Generator.) The space is ventilated, and the degree of ventilation is determined quantitatively. Liquid nitrogen dewars are present in proximity to purge the system. Another confined space houses a 50 kW PEM fuel cell (from Plug Power). This fuel cell system was designed to be load following and has the capacity to meet the electricity demand of about 30 homes.

Next in line to these units are a system air compressor and the main control panel, which integrates all the operations. The control system is monitored/operated by trained staff remotely from Allentown, PA (APCI's home office), or from Sacramento (operating plant/staff location). APCI has much larger systems that they currently operate remotely.

The five-stage hydrogen compressor is standard equipment. It takes ca. 6 bar (85-100 psi) hydrogen and compresses it up to ca. 350 bar (5000 psi). It is a manifold system with pressure relief devices (PRD) that vent to a safe location.

Backup hydrogen is purchased as a liquid and stored in a 5.7 m³ (1500 gallon), double walled tank, with a stainless steel internal shell and an external carbon steel shell. The tank is compliant with NFPA Standard 50B for liquid hydrogen and is located on a concrete pad rather than one composed of asphalt or similar organic material, which could act as a fuel in the event of a liquid hydrogen spill and subsequent ignition. (Since liquid hydrogen is cold enough to condense oxygen from the air, liquid oxygen dripping on asphalt would also provide ingredients for a fire.) Boil-off from the liquid hydrogen tank is used in vehicles.

The piping for hydrogen and CNG are compliant with ASME codes, and venting stacks are located in a safe, out of the way area. Piping is sized for the maximum calculated flows.

Maintenance of the system is performed by APCI staff from Sacramento or Phoenix, who visit regularly. If anything is detected to be “out of the ordinary” the system is shut down. (It is actually more likely that the automated control system would have already shut the system down.) A shutdown might only affect the part of the system that needs to be isolated.

Two dispensers are located next to each other just outside the fenced-off area, creating a fueling area. One dispenses pure hydrogen, while the other dispenses a blend of 65% CNG/35% hydrogen. Both dispense at 250 bar (3675 psi), but the geometry of the respective nozzles for the two dispensers are very different so a user cannot make an error.
A pressure meter is located on the outside of the hydrogen dispenser housing. The sensor monitors the purge inside the dispenser enclosure and, as such, can sense pressure increases or decreases inside the dispenser housing. For instance, if one pushes on the outside of the dispenser casing, a definite needle deflection can be seen on the meter.

The hydrogen/natural gas blending dispenser enables refueling similar to today’s gasoline refueling. The main difference is connecting the nozzle and receptacle. The connection is secured by rotating the handle 180 degrees.

In order to dispense hydrogen fuel into a vehicle a series of operations must be performed by the user, beginning with the input of a “PIN” number. There is, as with any hydrogen vehicle refueling, an option for the user to ground their vehicle through a cable. The nozzle is then connected with the vehicle receptacle and the lever is turned 180 degrees. At the end of fueling, the display indicates “end of fill” and the nozzle can be removed by rotating the lever.

Should the driver of the vehicle accidentally drive away with the nozzle and hose still locked in place on the vehicle’s fill-port, the hose has breakaway capabilities (according to SAE J2600). The station has had problems with system reliability, and characterized by some users as “spotty”. One of the main reasons for the reduced performance was the station’s infrequent use. During the site-visit in March 2004, the Annex 18 group witnessed the fueling of a pickup truck that runs on natural gas/hydrogen blends. The truck, a Ford F150 XL with a Triton V-8 engine was filled over a period of several minutes without mishap. Aside from this truck, the blend dispenser also services one bus.

10.4 System Operating Conditions

The basic technical data for the main pieces of equipment in the Las Vegas hydrogen energy system, together with some of their key parameters, is provided in Table 7. A description of the system operation is described below.

The reformer works best under constant demand, so under ideal conditions, the fuel cell would take about 50-60% of the output, and the remainder would either go to storage, or to be blended with natural gas. Thus, the reformer is able to operate steadily. However, the system can be run as low as 50% of its rated capacity. In this way, the fuel cell is kept operational, and there is no excess hydrogen available for storage or fueling.

It takes 8-12 hours from start-up to get high purity hydrogen. Start-up is not now a limiting factor, because one can design to fleet size and use storage (liquid hydrogen) as a backup.

The product from the PSA, at 6-7 bar (100 psi), is 99.95-99.99% pure, and contains less than 1 ppm CO and less than 2 ppm CO₂. There is no more than 100 ppm of any single impurity. Air Products has kept the system running for up to two weeks at a time. Reliability is still somewhat of an issue.

The Plug Power fuel cell ran for a total of about 2500 hours, sometimes at full peak and sometimes at partial load. Thus, a load-following system was successfully demonstrated.
Table 7 Main components in Las Vegas Hydrogen Energy Station

<table>
<thead>
<tr>
<th>Component</th>
<th>Parameters</th>
<th>Other Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen generation:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steam methane reforming</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Syngas compression</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure swing adsorption</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CNG feed</td>
<td>Running at 50% capacity will service FC only</td>
</tr>
<tr>
<td></td>
<td>H₂ production: 147 kg/day at 7 bar (100 psi) and 99.95-99.99% purity</td>
<td>Quantitatively ventilated</td>
</tr>
<tr>
<td></td>
<td>8-12 hours from start up to high-purity H₂</td>
<td>UV/IR detection</td>
</tr>
<tr>
<td>Five-stage reciprocating compressor</td>
<td>Power: 45 kW (60 hp)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Suction: 3.5 bar (50 psig)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Discharge: 370 bar (5400 psi)</td>
<td></td>
</tr>
<tr>
<td>High-pressure hydrogen storage tubes</td>
<td>360 bar (5200 psi) for 250 bar (3600 psi) fueling</td>
<td>ASME Stnd VIII</td>
</tr>
<tr>
<td></td>
<td>Total storage capacity: 127 kg H₂</td>
<td>NFPA 50A compliant</td>
</tr>
<tr>
<td>Liquid hydrogen storage tank</td>
<td>5.7 m³ (1500 gallon) tank</td>
<td>ASME Stnd VIII</td>
</tr>
<tr>
<td></td>
<td>Cryogenic, double-walled, vacuum annular space</td>
<td>Tank is filled twice a month</td>
</tr>
<tr>
<td></td>
<td>SS inner jacket</td>
<td>NFPA 50B compliant</td>
</tr>
<tr>
<td></td>
<td>Full inventory: 400 kg H₂, “low” loss rate</td>
<td></td>
</tr>
<tr>
<td>CNG/H₂ blending system</td>
<td>65/35 CNG/H₂ blend</td>
<td>Uses ASME codes</td>
</tr>
<tr>
<td></td>
<td>Mass-flow meter dynamically blends components</td>
<td></td>
</tr>
<tr>
<td>Blend dispenser</td>
<td>Customized dispenser from Krause unit</td>
<td>Positive engagement, break-away mechanism on hose</td>
</tr>
<tr>
<td></td>
<td>Dispenses to 250 bar (3600 psi) fueling</td>
<td>Automatic shut-off if loss of containment</td>
</tr>
<tr>
<td>Pure H₂ dispenser</td>
<td>Similar to blend dispenser, only built by APCI, and different geometry</td>
<td>Positive engagement, break-away mechanism on hose</td>
</tr>
<tr>
<td></td>
<td>Dispenses to 250 bar (3600 psi) fueling</td>
<td>Automatic shut-off if loss of containment</td>
</tr>
<tr>
<td>PEM Fuel Cell</td>
<td>50 kW unit, manufactured by Plug Power</td>
<td>Can generate electricity for up to 30 homes</td>
</tr>
<tr>
<td></td>
<td>Requires 50% of generated hydrogen</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Designed to be load-following</td>
<td></td>
</tr>
</tbody>
</table>

At the time of this visit, the hydrogen station was being used almost entirely for filling two vehicles, a truck and a bus, that run on hydrogen/natural gas blends. There were no fuel cell vehicles regularly utilizing this station, and in fact, the station was used for this purpose only.
at the plant dedication in 2002, and twice since then. One vehicle that was filled there was the Ballard fuel cell bus being used by SunLine Transit (Palm Springs, California). Hydrogen and natural gas are stored separately, never as a blend.

The dispensers are placed on concrete, which is an adequate grounding medium. However, people dispensing hydrogen or blends must touch a piece of equipment to ground themselves.

The control system uses Automated Programmable Logic Control (APLC) via satellite telemetry. The system considers human/machine interfaces, and has remote-asset monitoring capability. Innovative control logic was used in the engineering design.

The system operates at high summer (desert) temperatures and sees some freezing in the winter. Operability, reliability, and economic feasibility data have not been made available to Annex 18, but were obtained at the end of the first two-year phase (2004).

10.5 Safety Considerations

The safety design, in accordance with the project leaders (APCI) historical safety practices and operating experience, was geared toward a statistical level of success. However, experience is that the safety planning of each of APCI’s installations (of which the Las Vegas facility is one) cannot be reduced to the same checklist, as each station is somewhat different. This demonstrates that hydrogen fueling technology is not yet sufficiently mature to have a standard checklist.

The hydrogen station in Las Vegas adopted APCI’s philosophy for inherently safe systems surrounded by protective systems. In order to achieve safe operations, it is always useful to ask the question ‘what might the average person do?’

The key components of APCI’s safety methodology include:

- Mechanical integrity
- Mechanical pressure-relief devices
- Safe locations for vented gases with minimized flow distances
- Personal protective equipment (although not much is needed in this instance)
- Instrumental control systems designed to safely shut down the system prior to unsafe conditions manifesting themselves

In order to identify safety vulnerabilities a HAZOP-method developed by APCI (as part of a Management of Change package) was used. This HAZOP-analysis includes consideration of the interface with the customer or end user. Representatives of the end user (in this case the City of Las Vegas) were included in the analysis team. Pressure, temperature, flow, composition, metallurgy, and operator use are used as key safety parameters. When a potential hazard is identified, the project leader (APCI) relies on their experience and knowledge to address it. If necessary (which has not yet been the case in Las Vegas), a fault tree or failure modes and effect analysis can be used to solve a problem. A statistical risk analysis itself is based on an empirical experience and scientific knowledge.

Some of the specific safety features of the system include:

- ASME-code compliant steel (not composite) hydrogen storage vessels
- A hydrogen dispenser nozzle compliant with SAE J2600
• Distinctly different geometries for the hydrogen and blended-fuel dispenser nozzles so that they cannot be mistaken for one another
• Automatic pressure-loss checks prior to and during a fueling operation
• Concrete platforms in the fueling areas to promote grounding
• Third-party-certified electrical enclosures

It could also be mentioned that cone-and-thread fittings for high-pressure mechanical connections were also added, even though the system is designed to minimize the mechanical connections as a whole.

10.6 Conclusions

The Las Vegas Hydrogen Energy Station demonstrates how dual-purpose (fuel and stationary power production) and multi-fuel (pure H\textsubscript{2} and H\textsubscript{2}/CNG blends) integrated hydrogen system based on natural gas (NG) can be designed and operated. In summary, the following main conclusions can be made:

• **Operation**: Constant reformer operation with the possibility of 50% part load operation provides a flexible overall system design. The ideal operation is to use 50% of the hydrogen produced directly in the stationary fuel cell and send the rest to the dispenser and storage system.
• **Reliability**: Poor system reliability was achieved due to infrequent use of station.
• **Safety**: Hydrogen fueling technology is not yet mature enough to have a standard safety checklists. Extensive safety measures were required in the form of warning signs, fences, unique nozzle geometries, hose breakaway capabilities, etc.
• **Standardization**: It was difficult to make a standard system due to lack of hydrogen purity standards. The Las Vegas Hydrogen Energy station was designed for 99.95-99.99% pure hydrogen, while many of the other 12 hydrogen stations in California and Nevada had different hydrogen purity demands.

10.7 Future Plans

The Las Vegas Energy Station moved into phase 2 at the end of 2006, with the addition of more vehicles; passenger cars, shuttle buses, and mixed fuel trucks. A satellite fueling station will also be constructed at a separate location in the city. Air Products has several hydrogen fueling stations (three dispense hydrogen/natural gas blends) in California. The plan is to integrate the Las Vegas Energy Station with the stations in California and another station in Phoenix.
11 Hydrogen Fueling Station in Reykjavik (Iceland)

11.1 Introduction

Water electrolysis based on hydroelectric power is one of the cleanest and most environmentally methods for hydrogen production. Distributed water electrolyzers is by many (e.g. IEA HIA) viewed as one of the best ways to build the market for the future hydrogen economy (Figure 42), as this can be based on fairly well-developed technology [30].

![Figure 42 Scenario for most probable development of a hydrogen economy, with focus on building an infrastructure for hydrogen stations [30].](image)

In Annex 18 three electrolyzer-based hydrogen fueling stations were evaluated in some detail:
1. Hydrogen fueling station in Reykjavik, Iceland (ECTOS) [2]
3. Pacific Spirit Station (PSS) in Vancouver, Canada [6]

At the start-up of Annex 18 (in 2004) the hydrogen station in Reykjavik, namely the ECTOS-project (Ecological City Transport System), had received a significant amount of attention in the media, but no independent technical evaluation had been performed. Since the ECTOS-project was so successful, and also could provide operational data, it was in Annex 18 decided to take a detailed look at the design and operation of this particular hydrogen station.

The hydrogen stations in Malmö and Vancouver were not evaluated in detail in Annex 18, but are included in this report for completeness. The NG/H₂ buses in Malmö get their hydrogen from an electrolyzer, and therefore represent an interesting concept for building a hydrogen infrastructure in a cost-efficient manner. The hydrogen station in Vancouver was originally designed for electrolyzer operation (not operational any more), and includes a novel and interesting multi-pressure hydrogen compression system. Hence, it was decided in Annex 18 to include these two systems in the overall evaluation of electrolyzer based hydrogen stations.
11.2 Background

In 1997 a committee appointed by the Icelandic Ministry of Energy to investigate the possibility of domestic fuel production, such as hydrogen. As a result, Icelandic New Energy Ltd. was formed in 1999, owned partly (51%) by a national consortium (Icelandic New Business Venture Fund, Icelandic energy companies, and academic institutions, registered as VistOrka) and partly (49%) by three international companies (Daimler-Chrysler, Norsk Hydro, and Shell Hydrogen).

Shortly after the establishment of the company, Icelandic New Energy began the preparation of the ECTOS (Ecological City TranspOrt System) demonstration project. This project finally received 2.85 million EUR (total cost of 7 million EUR) from the Fifth Framework Programme of the European Union (EU). The 4-year ECTOS project was launched on 1 March 2001. The first two years (phase 1) of the project involved preparation, establishing infrastructure and a maintenance facility, training of staff, development of a methodology for socioeconomic impacts’ research, etc. The latter two years (phase 2) involved the actual demonstration of three hydrogen buses and running a commercial infrastructure, and was later expanded into the Hy-FLEET:CUTE until 2007.

The two overall objectives with the ECTOS-project were to:
- Construct a hydrogen fuelling station completely integrated into an urban setting
- Feed three hydrogen fuel cell buses in the regular public transport fleet of Reykjavik for a test period of at least two years.

The infrastructure preparation involved building a hydrogen production, compression, and refueling station, and operate this as a pre-commercial Shell fueling station on the outskirts of Reykjavik. The hydrogen station is equipped with an alkaline electrolyzer from Hydro operating on power from the municipal grid and water from the municipal water network. The system can deliver gaseous hydrogen (after compression) at 440 bars. The total production capacity of the plant is about 200 kg/day, and the dispenser is capable of delivering ca. 40 kg of hydrogen in ca. 7 minutes (Figure 43 and Figure 44). A fuel monitor regulates the filling automatically and keeps the pressure within limits, to avoid damage to hoses, cylinders, or fittings.

Three Fuel Cell Citaro busses from EVO-BUS (daughter-company of DaimlerChrysler) were delivered to Iceland in August-December 2003. The buses were powered by a 250 kW PEM fuel cell system from Ballard. The fuel cell gets its hydrogen from 350 bar storage units located on the roof (together with the fuel cell). The buses were operated in normal routes within the Reykjavik public transportation system from October 2003 to January 2007. After this test period was over, and the buses were dismantled. The buses had a driving range of 150-240 km, depending on the drive cycle. In order to avoid freezing of the fuel cell system overnight, the buses were either parked inside or warmed during the night by electric power from the municipal grid. A comprehensive case study of the ECTOS-project was performed in 2005 as part of Annex 18 [2].

The main objective with the work undertaken in Annex 18 Subtask B was to develop, test, and verify a generic hydrogen station simulator that can be used to investigate alternative system designs and refueling scenarios for similar electrolyzer based hydrogen stations.
Figure 43 Photos of the hydrogen fueling station for the ECTOS-project demonstrated in Reykjavik, Iceland.

Figure 44 Schematic of the hydrogen fueling station for the ECTOS-project demonstrated in Reykjavik, Iceland.
11.3 Site Visit to Hydrogen Station in Reykjavik on 5 September 2005

On 5 September 2005 the Annex 18 group was offered a technical tour of the hydrogen fueling station and the bus maintenance facility at the milk factory garages near the Shell station on the outskirts of Reykjavik, Iceland. After an introduction to the ECTOS-project by Jón Björn Skúlason of Iceland New Energy Ltd., the participants were treated with a ride on one of the hydrogen buses to the site. A temporary stop of the hydrogen station (due to service) made it possible for the IEA-group to take a closer look (than otherwise would have been possible) at the individual system components located inside the concrete enclosure (Figure 43).

A visit to the nearby bus maintenance facility (dairy truck service facility redesigned for hydrogen operations) was also made. The IEA-group was given insight to how the three Daimler-Chrysler city buses have been fitted with Ballard Fuel Cells. Modifications on the buses to handle the hydrogen and fuel cells were also pointed out, such as the strengthening of the roof to carry extra load. Local personnel shared their experiences on what is involved in getting the buses to operate in routine city service. The feedback from users of the buses is positive, and local residents have been very happy to ride the quiet buses. This result is in agreement with the socio-environmental studies performed by María H. Maack, who also served as an excellent the guide for the entire technical visit.

11.4 System Description

The hydrogen fueling station in Reykjavik is primarily designed to meet the hydrogen demand for three fuel cell buses. The nominal ratings, capacities, and key characteristics of the main hydrogen system components in the ECTOS-project (Figure 44) are as follows:

- Water electrolyzer: 60 Nm$^3$/h (128 kg/day), 15 bar, alkaline
- Compressor: 15-500 bar, mechanical two-stage, oil-free diaphragm
- Hydrogen storage: 27 Nm$^3$, 440 bar, three-stage decanting system
- Dispenser: 40 kg in ca. 7 minutes
- Fuel cells on buses: 3 × 250 kW, PEM fuel cells

The main auxiliary equipment for the electrolyzer balance of plant (BOP) is the cooling tower and the gas purification system. The purification system consists of a deoxidizer and a twin tower dryer, which removes traces of oxygen and moisture in the gas. Bottled nitrogen (N$_2$) is used to purge the system before start-up and after shutdown. The water electrolyzer with purification and drying equipment is all enclosed in a 9 m long container (Figure 43).

The system gets all of its electricity and fresh water from the municipal grid (82% hydroelectric power and 18% geothermal power) and water network, and produces all hydrogen in situ. On the electrical side it should be noted that a specially designed transformer was required to step down the incoming AC voltage to ensure proper input voltage to the rectifier (AC/DC-inverter). Water treatment was, on the other hand, much simpler, as the water from the city’s water-network was very clean and contained unusually low concentrations of minerals.

The first dispenser installed at the station had some problems and failed to deliver a pressure of 350 bar to the vehicles. Thus, a new dispenser was developed (by Norsk Hydro) and installed in 2004. The new dispenser communicates the vehicle pressure and temperature...
hydrogen gas expands due to an increase in temperature during filling), and the fueling procedure is slowed down automatically to avoid overloading (too high pressure). More details on the hydrogen station and fuel cell buses in Reykjavik is found in the Annex 18 case study [2].

11.5 Evaluation Methodology

The hydrogen fueling station in Reykjavik was designed to produce, compress, and dispense hydrogen \textit{in situ}. This meant that special attention was made towards designing and building a robust and inherently safe system, ensuring high regularity on the operation. As a consequence there was less focus on designing and building an energy efficient system. This was taken into account in the evaluation performed by the Annex 18 group.

The main objective with the work performed within Annex 18 on electrolyzer-based hydrogen stations was to develop a generic hydrogen fueling station simulation model based on actual operational data. Due to the availability of operational data from the hydrogen station in Reykjavik, it was decided to take a closer look at the design and operation of this station.

The evaluation methodology selected in Annex 18 was to:
1. Develop hydrogen station simulation model
2. Verify models for main components
3. Verify overall electrolyzer system model
4. Determine typical hydrogen demand profile
5. Simulate existing operational scheme in detail
6. Simulate and evaluate two new and different hydrogen station operating regimes:
   a) Increase electrolyzer run-time by allowing for more part-load operation of electrolyzer
   b) Increase hydrogen demand by introducing more buses and/or cars

It should be noted that the most significant inefficiencies in electrolyzer based hydrogen stations, such as the one installed in Reykjavik, is associated with inefficient system operation and not necessarily with the nominal efficiency of the electrolyzer itself (energy consumption is typically around 5.5 kWh/Nm$^3$). A specific feature of this type of pressurized alkaline electrolyzers is that when they are shut down, they need to be depressurized (in this case from 15 bar to 1 bar) and the gas system (oxygen and hydrogen side) needs to be purged with an inert gas, normally nitrogen. It should be noted here that new and more advanced alkaline electrolyzers kept under constant pressure [31] will not have this problem$^2$.

Frequent use of nitrogen to purge excess hydrogen and water vapor is inefficient and costly. In other words, it is more efficient and economical to produce hydrogen for longer periods of time, instead of shutting down the process due to low hydrogen demand at the dispenser. Practical experience from the operation of the actual system in Reykjavik demonstrated that the electrolyzer frequently needed to be shut down, due to a mismatch between hydrogen production and hydrogen demand (oversized electrolyzer).

$^2$Note: A new and more advanced 30 bar alkaline electrolyzer has been developed (GHW-technology, now fully owned by Hydro). This electrolyzer can keep the pressure during shutdown, which prevents oxygen from entering the system and removes the need for frequent purging with nitrogen. This new technology will probably be the preferred technology for future alkaline electrolyzer based hydrogen fueling stations.
Adding two or more hydrogen vehicles to the fleet in Reykjavik would therefore make the operation more efficient and economical. An alternative to expanding the vehicle fleet is to operate the electrolyzer more frequently on part-load, thus avoiding frequent shut down. This is the background for the two different operating regimes studied in Annex 18. These are described in the list above (6a and 6b), and discussed in further detail below.

11.6 Hydrogen Fueling Station Simulator

The hydrogen fueling station simulator developed in Annex 18 (Figure 45) was developed from scratch using existing HYDROGEMS-models, the EES-program, and data from the ECTOS-project in Reykjavik, Iceland.

Figure 45  Main diagram window (in EES) for the electrolyzer-based hydrogen fueling station simulator developed in Annex 18.
11.7 Analysis of Operational Data and Verification of Models

Operational data from 2005 was used to verify the main components and overall hydrogen refueling station simulation model (Figure 46). The data was specifically used to find the electrical characteristics \((IU\)-curve\) of the electrolyzer and detailed information on the power capacities of the auxiliary system components for the balance of plant (BOP) in place at the refueling station in Reykjavik.

A closer look at the electrolyser energy consumption per unit hydrogen produced, indicates that there is a slight mismatch between the calculated and anticipated values (respectively, 5.3 kWh/Nm\(^3\) versus 5.0 kWh/Nm\(^3\)). The exact cause of this mismatch is unclear, as the coefficients for the empirical \(IU\)-model were calibrated based on measured data from the actual operation of the electrolyzer.

Another challenging modeling task was to estimate the actual compressor work based on the monitoring data available, and to verify the theoretical model. Here, the most likely source of error is the hydrogen mass flow rate, which is not measured, but calculated based on the temperature and pressure. Hence, a separate detailed study of a hydrogen compression system should be undertaken. One clear candidate within the Annex 18 project portfolio is the compressor system built at the Pacific Spirit Station in Vancouver (described in more details below).

Analysis of data from the Reykjavik hydrogen station was performed as part of a MSc study at the University of Iceland. The data analysis shows that there is some uncertainty in the estimated energy demand for some of the hydrogen system components (BOP) in hydrogen station in Reykjavik, particularly for the hydrogen compressor. However, information on the installed power capacities and typical component run-times for the various system components (Figure 46) can be used to estimate theoretical maximum energy demands on a more general basis (Figure 47).

From Figure 46 it can be deducted that the BOP accounts for about 8% of the total rated power capacity (kW) of the overall system (electrolyzer + BOP), and 15% if the compressor is included. The corresponding energy values (kWh) are difficult to determine, as this is highly dependent on the operation of the system, but first approximations based on measured data show that the equivalent values are 9% (without compressor) and 17% (with compressor).

The hydrogen demand at the dispenser (Figure 48) is one of the most crucial time dependent variables affecting the design and operation of any given hydrogen station. Hence, the hydrogen station simulator was designed so that it was easy to enter different hydrogen demand profiles (simulation forcing function).
Figure 46 Rated power capacities and no. of operating hours for the individual system components of the balance of plant (BOP) installed at the hydrogen fueling station in Reykjavik, based on data for a typical week in 2005.

Figure 47 Relative energy demands in the balance of plant (compressor work not included) for the hydrogen station in Reykjavik, based on data for a typical week in 2005.

Figure 48 Hydrogen demand at fueling station in Reykjavik in June 2005.
11.8 Application of the Model (Simulation Study 4)

The main objective with simulations described below (Figure 49 - Figure 51) was to demonstrate how the fueling station simulator developed in Annex 18 (Figure 45) can be used to evaluate two alternative operating regimes and hydrogen demands suitable for the Reykjavik hydrogen station.

An alternative operation of the hydrogen station in Reykjavik is to operate the electrolyzer continuously. For the relatively low hydrogen demand (Figure 48) this is only possible if the electrolyzer is allowed to idle for longer periods of time. Figure 49 shows how the hydrogen production and pressure in the hydrogen storage develops over a typical week, if the electrolyzer was allowed to “idle” at 25% of its nominal power.

Figure 49 shows how the pressure in the hydrogen storage gradually builds up over time, and how infrequently the electrolyzer is operating. The simulation results indicate that there could have been a much better balance between supply and demand of hydrogen, and that a much smaller electrolyzer probably could have supplied the same amount of hydrogen. However, it should be noted that a reduction in the electrolyzer production capacity could lead to a need for a larger hydrogen storage. No alternative designs were investigated in this study, and is left for future work.

An alternative hydrogen demand profile was investigated in the next set of simulations. One approach is to allow for weekend operation of the three buses (Figure 50). Another approach is to simply add two new buses (no weekend operation) (Figure 51). The results from both of these two simulations show that there is plenty of extra hydrogen production capacity that can be utilized at the existing hydrogen fueling station in Reykjavik.

The results in Figure 50 shows that the buses also should be operated over the weekends, as this would create a much more frequent operation of the electrolyzer. Adding two new buses would be very costly, and is probably not a very realistic alternative at this stage. Thus, special attention should be made towards finding an optimal hydrogen fueling regime. This optimization needs to take into account practical considerations, such as service intervals for the buses etc.
Figure 49 Simulation Study 4: Alternative operation of the hydrogen station in Reykjavik, where part-load electrolyzer operation (idling at 25% of rated power) is permitted.

Figure 50 Simulation Study 4: Alternative hydrogen demand profile for station in Reykjavik, where the three (3) buses also are operated over the weekends.

Figure 51 Simulation Study 4: Alternative hydrogen demand profile for station in Reykjavik, where the five (5) instead of three (3) buses are operated during the week.
11.9 Conclusions

An electrolyzer-based hydrogen fueling station has been built in Reykjavik, Iceland, and three hydrogen-based fuel cell buses were successfully operated from October 2003 to January 2007. The operation of the hydrogen fueling station and buses proceeded without any major problems or unexpected incidents, which means that there is lot to learn from the project from a practical point of view. This is reported in a separate Annex 18 case study.

Several conclusions on the design and operation of the hydrogen fueling station in Reykjavik can be made from the technical evaluations and simulations performed within Annex 18 Subtask B. These are summarized below.

Data Collection and System Analysis:
- Operational data from hydrogen station was collected and analyzed. This data included performance of the electrolyzer and the balance of plant (BOP); namely, sub-systems for heating, cooling, ventilation, pumping and compression.
- The operational data could be used to verify the current-voltage characteristics of the electrolyzer, but could not be used to verify in detail the energy consumption of the individual component in the BOP. This was particularly true for the hydrogen compressor.
- Due to the lack of sufficiently detailed data, several approximations on the BOP needed to be made based on rated power capacities and no. of operating hours for the individual system components of the balance of plant.

System Design:
- Analysis of the existing data shows that the hydrogen station has a fairly low overall system efficiency, due to the relatively large balance of plant and inefficient electrolyzer operation.
- System simulations confirm that the electrolyzer and hydrogen storage is over-designed for the given hydrogen demand. This yields very few operating hours for the electrolyzer.

System Operation:
- System simulations show that the overall system efficiency can be significantly improved by allowing the electrolyzer to idle instead of being shut down.
- System simulations show that a very small part of the hydrogen storage capacity is used, which indicates that a much smaller hydrogen storage could have been installed.
- Separate data analysis shows that the main energy consumers in the BOP are the hydrogen compressor and cooling units.

General Comments & Recommendations:
- The hydrogen station in Reykjavik was on of the first in the world of its kind and was designed to extremely robust, safe, and reliable. This explains the over-design of the electrolyzer and the hydrogen storage. A smaller system is recommended.
- Detailed investigations on a more flexible hydrogen storage and compressor system with a smaller hydrogen storage and a boost compressor are recommended.
12 Hydrogen Fueling Station in Malmö (Sweden)

12.1 Background

In 1985 Sydkraft and the Municipality of Malmö started a long-term collaboration on the conversion of diesel driven city buses to compressed natural gas (CNG) busses. Currently more than 330 buses, 80 trucks, and 1000 cars are running on CNG and biogas in the region of Skåne, including Malmö.

The quest for testing new alternative fuels for vehicles is continuing in Malmö. The effort has lead to the development of a hydrogen station capable of delivering pure hydrogen for demonstration vehicles and various mixtures of hydrogen and natural gas for the local city buses (Figure 52 and Figure 53).

The hydrogen station was originally developed, built, and operated by Sydkraft. It started operation in September 2003. In 2006 E.ON took over Sydkraft, and E.ON Sverige Gas AB (the largest private utility company in Sweden) is now in charge of the operation and further development of the station. Grontmij AB (formerly Carl Bro Energikonsult AB and Sydkraft Consult) has been an active partner in the Malmö hydrogen filling station project, from the very first idea to the design, project management, procurement, start up of the filling station, and finally with the follow-up of the operation of the plant and the buses.

The results after two years of operation of the city buses using different mixtures of CNG and hydrogen, ranging from 8 vol% to 20 vol% H₂, have been encouraging [5]. Blends with 25 vol% H₂ were also tested. The challenge is now to continue to expand the test program and use the optimal mixture of hydrogen and natural gas in a greater number of buses, and also to increase the number of pure hydrogen vehicles in the project.

This was the background for doing a special analysis of the Malmö hydrogen natural gas bus station concept (Figure 53) within the Annex 18. The data used in this analysis was primarily based on experimental data from the Institute of Technology at Lund University and Carl Bro Energikonsult AB.

The main objective with the work undertaken in Annex 18 Subtask B was to calculate the overall efficiencies and emissions of internal combustion bus engines running on natural gas hydrogen mixtures (8-25 vol% hydrogen), the overall emissions for a larger natural gas hydrogen bus fleet, and the corresponding hydrogen demand at the fueling station. A special hydrogen station calculation tool was developed to this end.

12.2 Site Visit to Hydrogen Station in Malmö on 21 August 2004

No official Annex 18 visit was made to the hydrogen station project in Malmö, Sweden. However, in order to kick-start the abovementioned analysis the Subtask B leader from IFE visited the Malmö fueling station and the combustion engine laboratories at the University of Lund on 21 August 2004, and discussed technical issues with project representatives from Carl Bro Energikonsult and the University of Lund.
Figure 52 Photos of the hydrogen and natural gas fueling station in Malmö, Sweden.

Figure 53 Schematic of the hydrogen and natural gas fueling station in Malmö.
12.3 System Description

In Malmö the hydrogen is produced on-site via water electrolysis, and in direct connection to the filling station (Figure 53). The electricity is produced in a nearby wind power plant and distributed to the plant via the electrical grid. Hydrogenics in Belgium and Canada supplied the hydrogen plant, including the production and filling station.

Technical data for the electrolyzer as stated by the supplier:
- Capacity: 36 Nm$^3$ H$_2$/h
- Power consumption electrolyser: 4.2 kWh/ Nm$^3$ H$_2$/h
- Power consumption in total: 5.5 kWh/ Nm$^3$ H$_2$
- Water consumption: 36 l/h
- Pressure from electrolyser H$_2$: 10 bar
- Power requirement: 210 kW
- Power load area: 25 - 100 %

The electrolyser unit and the hydrogen storage are placed in an industrial area close to the filling (Figure 52). The hydrogen storage is placed closed to the electrolyser unit. Dynatech, Canada, delivered the hydrogen pressure vessels. The hydrogen is stored ca. 350 bar (maximum 440 bar) and the total volume of the storage is 4 m$^3$.

The dispenser is delivered by FTI, Canada. It consists of two hoses, one for pure compressed hydrogen and the other for the mix of hydrogen and CNG. The mixture is done in the dispenser directly while filling the vehicle fuel tank.

The three different fuelling options at the dispenser are:
- Compressed hydrogen at 350 bar
- CNG with 8 vol% hydrogen
- CNG with 20 vol% hydrogen

The background to use these fuelling options is:

**Hydrogen at 350 bar** is a standard often used for fuel cell vehicles. DaimlerChrysler Evobus has specified 350 bar as onboard storage for the hydrogen fuel on their Citaro buses used in the CUTE and other similar projects. It is also the standard for DaimlerChrysler FCell fuel cell cars and several other modern demonstration vehicles using hydrogen as fuel.

**CNG with 8 vol% hydrogen** is a lean mixture of hydrogen into the CNG. This is considered as CNG according to the specification of natural gas. The mixture can be used directly in the current CNG city buses without any modifications of the fuel system or engine set points or hardware.

**CNG with 20 vol% hydrogen** has a larger portion of hydrogen, which means that a larger portion of the fuel can be produced locally and more environmental benefits can potentially be achieved. This heavier mix of hydrogen into the CNG cannot be considered as natural gas. Hence, a modification of the internal combustion engine set points for ignition and fuel injection is required, and a comprehensive safety check of the fuel system of the buses needs to be performed.
12.4 Evaluation Methodology

In general, the objective to use a mixture of CNG and hydrogen is to:
• Improve the efficiency and operation of the internal combustion engines
• Decrease emissions, both local emissions and CO2
• Enable the use of a locally produced fuel

The purpose of including the Malmö fueling project in the Subtask B portfolio was to use the measured and calculated efficiencies to build a simulation tool to estimate the total emissions and hydrogen demand for a larger bus fleet. This tool could also be used for sizing the enlarged station and to estimate the overall emissions.

The specific approach taken was to:
1. Assume 100% renewable energy based hydrogen production via water electrolysis
2. Evaluate the effect of a specific drive cycle with respect to
3. Efficiency and fuel consumption (NG and/or H2)
4. Emissions (CO2, NOx and HC)
5. Compare results based on NG only with those based on NG/H2-mixes
6. Extrapolate the results to 100-200 buses

12.5 Experimental Data on the Efficiency and Emissions of CNG/H2-Engines

Two buses in the local bus fleet in Malmö have used CNG with 8 vol% of H2 as fuel without any modifications of the lean-burn CNG engines. The Institute of Technology at Lund University, Sweden, has confirmed significant improvements in fuel efficiency, more stable operation of the engine and reduction of emissions by performing bench testing of the engines. Measurements of efficiency, emissions, combustion variations, knocking etc. have been performed during different conditions, as shown in Figure 54.

![Figure 54 Brake efficiency (%) at different air/fuel ratios for an engine running on CNG with 8 vol% of H2 versus an engine running on pure CNG (lambda = air/fuel ratio).](image-url)
The results (Figure 54) show that the brake thermal efficiency increases when hydrogen is mixed into the CNG fuel, when compared to pure CNG. This can be explained by the fact that the duration of the combustion is reduced when hydrogen is added to CNG. The effective expansion ratio increases with a faster combustion, and more work can be extracted from the gas.

The most significant increases in efficiency can be achieved on natural gas engines with relatively slow combustion, i.e. lean burning conditions. The Volvo TG100 engines used in the local city in Malmö are lean burning engines, and their performance could possibly be improved by adding hydrogen to the CNG fuel. The increase in efficiency, together with the reduction of the carbon content in the fuel, decrease the emissions of CO₂ substantially when hydrogen is used as a fuel additive, as shown in Figure 55.

The addition of hydrogen to CNG creates a faster combustion, and more efficient combustion, compared to pure CNG. Lower emissions of HC and CO are achieved, as the combustion is more efficient. The higher combustion temperature can though increase the NOₓ emissions. This can be avoided by using a higher air/fuel ratio and/or less spark advance.

In summary, the Volvo TG100 engine experiments performed in the laboratory at the University of Lund showed that CNG/H₂-mixtures with 8 vol% hydrogen gave the following results:

• Higher efficiency
• More stable combustion, due to a faster combustion (less cycle to cycle variations)
• A slight increase in power output
• Lower HC and CO emissions because of higher combustion efficiency
• Higher or similar NOₓ emissions (with no changes applied to fueling or spark)
• Slightly higher knock tendency
Further tests on CNG with 20 vol% of H₂ were also performed in the laboratory. These tests showed significant improvements compared to pure CNG. The reduced combustion duration increased the efficiency significantly and enabled the reduction of NOₓ emissions by using a higher air/flow ratio combined with optimized ignition timing. The reduction of CO₂-emissions was also quite substantial.

The results from engine tests on CNG with 20 vol% of H₂ at different air/fuel ratios are shown in Figure 56. The plots show that there is a trade-off between HC and NOₓ emissions with respect to ignition angels. The engine tests also showed that extreme air/fuel ratios can lead to other problems, such as instable engines, or too high tendency of engine knock. However, since a 20% volume hydrogen mixture contains even less carbon it significantly reduces the amount of other harmful carbon emissions, particularly the CO₂ emissions.

![Figure 56 HC – NOₓ emissions (trade off) at different air/fuel ratios for an engine running on CNG with 20 vol% of H₂ versus and engine running on pure CNG.](image)

**12.6 Emission Measurement from Testing on the Road**

In August 2005 a bus was selected for emission testing on the road. All of the other measurements discussed above were done in an engine laboratory with an engine of the same type as that in place in the city buses, namely a Volvo TG100 lean burning engine. The bus was driven both on CNG with 20 vol% of H₂ and on pure CNG.

Four different the tests were performed,
1. Maximum power up a long uphill slope on a motorway during non rush hour conditions
2. Steady state driving on an old airstrip at velocities between 20 and 70 km/h
3. Idling of the engine
4. Start up from a bus stop and acceleration up to 40 km/h
The road tests included measurements of emissions, airflow, speed, and engine rpm. The results showed that the HC emissions were significantly reduced, while the NO\textsubscript{x} emissions were slightly higher for a hydrogen enriched fuel. This is not in agreement with results obtained in the laboratory. However, the laboratory experiments were performed at steady conditions, while the road tests gave non-steady operating conditions. The increase in NO\textsubscript{x} emissions can probably be avoided by introducing a more accurate mapping of the engine air/fuel ratio and ignition set points. Road test confirmed that the fuel consumption was significantly lower with the CNG/H\textsubscript{2} mixture (Hythane) compared to the pure CNG (due to increased efficiency), as shown in Figure 57.

![Graph] Figure 57 Road test fuel consumption for bus running on CNG with 20 vol\% of H\textsubscript{2} (Hythane) versus engine running on pure CNG.

12.7 CNG/Hydrogen Bus Engine and Station Simulation Model

In Annex 18 Subtask B a general CNG/hydrogen bus engine and station simulation model that calculates the fuel consumption, efficiency, and emissions for CNG/H\textsubscript{2} and pure CNG was developed. The purpose with the model was to:

- Compare the overall performance (efficiency and emissions) of buses running on CNG with 25 vol\% of H\textsubscript{2} to those running on pure CNG, based on a standard drive cycle.
- Estimate the average daily hydrogen demand for a given number of buses (e.g. 100-200 buses) with a given daily driving range (e.g. 150 km) and known fuel consumption.

The simulation model was based on fuel consumption curves derived from road tests (Figure 57), a standard European (ECE R49) drive cycle (Figure 58 and Figure 59), and detailed bus engine data from the University of Lund (Figure 60 - Figure 63). The drive cycles used as basis for the specific efficiency and emissions calculations was divided into 13 distinct load steps, and categorized according to low, medium, and high RPM (Figure 58). The drive cycle was combined with a typical loading on the engine (Figure 59). In other words, the value obtained for each load step (%) was multiplied by a weight factor (%).

The values for efficiency (%) and emissions (g/kg fuel) for specific loads (%) and RPMs were found by linear interpolation in tables containing experimental data for two specific fuels, pure CNG or CNG with 25 vol\% of H\textsubscript{2}. This data is plotted in Figure 60 - Figure 63. The
efficiencies and emissions for the overall drive cycle were simply calculated by summing up the values calculated for of the 13 load steps. These values could then be linearly extrapolated to estimate the total emissions and fuel consumption for a larger bus fleet.

Figure 58  The basic drive cycle used in the efficiency and emissions calculations, showing the typical loading on the engine (%) at different RPMs.

Figure 59  The basic drive cycle used in the efficiency and emissions calculations, showing the weight factor (%) used at different RPM, i.e., how frequently the engine is operated at the various loadings.
Figure 60  Efficiency as a function of load and RPM for an engine running on CNG with 25 vol% of H₂ versus an engine running on pure CNG.

Figure 61  CO emissions as a function of load and RPM for an engine running on CNG with 25 vol% of H₂ versus an engine running on pure CNG.
Figure 62 NOx emissions as a function of load and RPM for an engine running on CNG with 25 vol% of H$_2$ versus an engine running on pure CNG.

Figure 63 HC emissions as a function of load and RPM for an engine running on CNG with 25 vol% of H$_2$ versus an engine running on pure CNG.
12.8 Application of the Model (Simulation Study 5)

The main diagram window (including main results) for the Malmö CNG/H₂ station and bus engine simulator is shown in Figure 64. The main outputs here are the calculated total CNG and H₂ consumption and the CO₂ emissions. This is important information for the planning of the up-scaling of the hydrogen station and bus fleet in Malmö.

The hydrogen production demand calculated using the Malmö hydrogen station simulator (Figure 64) can be used as input for more detailed designs of up-scaled systems. Detailed system designs can be developed using the Reykjavik hydrogen station simulator (Figure 45). Hence, the two hydrogen station simulators developed in Annex 18 complement each other.

Figure 64 Main diagram window (in EES) for the Malmö CNG/hydrogen bus engine and station simulator (fuel consumption and emissions calculator) developed in Annex 18.
12.9 Conclusions

Experimental data on the efficiency and emissions of internal combustion engines running on CNG/H₂-mixtures was obtained from engine laboratory tests. The experiments showed that CNG with 8 vol% of hydrogen gave:

- Higher efficiency
- More stable combustion, due to a faster combustion (less cycle to cycle variations)
- A slight increase in power output
- Lower HC and CO emissions because of higher combustion efficiency
- Higher or similar NOₓ emissions (with no changes applied to fueling or spark)
- Slightly higher knock tendency

Engine experiments on CNG with 25 vol% of hydrogen gave similar results:

- Increased the efficiency
- Reduction in NOₓ emissions (higher air/flow ratios and optimized ignition timing needed)
- Reduction of CO₂-emissions (more hydrogen in fuel).
- Extreme air/fuel ratios can lead to instable engines, or too high tendency of engine knock

Separate road test using the same engine confirmed that the fuel consumption was significantly lower in buses using CNG with 20 vol% hydrogen (Hythane) compared to those using pure CNG.

In Annex 18 Subtask B a general bus engine model that calculates the fuel consumption, efficiency, and emissions for CNG with 25 vol% hydrogen and pure CNG was developed. The model was based on experimental data from engine tests, bus road test data, and a standard European drive cycle.

It was demonstrated that the model can be used to:

- Compare the overall performance (efficiency and emissions) of natural gas buses running on CNG with 25 vol% hydrogen to those running on pure CNG, based on a standard drive cycle.
- Estimate the average daily hydrogen demand for a given number of buses (e.g. 100-200 buses) with a given daily driving range (e.g. 150 km) and known fuel consumption.
13 Pacific Spirit Station (PSS) in Vancouver Canada

13.1 Background

The Pacific Spirit Station (PSS) in Vancouver (Figure 65 and Figure 66) is a partnership between the Canadian Transportation Fuel Cell Alliance (CTFCA) of Natural Resources Canada, BOC Canada Ltd. / Linde, General Hydrogen, the National Research Council’s Institute for Fuel Cell Innovation (NRC-IFC), and Fuel Cells Canada. This is the first multi-partner hydrogen filling station in Canada. The station is located in Vancouver British Columbia at the NRC-IFC on the campus of the University of British Columbia (UBC) [6].

The station was designed for hydrogen fuelled passenger vehicles such as cars and light trucks. The first users of the station are vehicles from the Vancouver Fuel Cell Vehicle Program (VFCVP). The VFCVP is managed by Fuel Cells Canada and consists of a three year evaluation of a fleet of five fuel cell powered Ford Focus vehicles under real world conditions. The station is presently servicing three of these vehicles. One of the others operates in Victoria and another vehicle is fueled at Powertech Labs in Surrey, BC.

The day to day operation of the station was taken care of by the NRC with support from BOC, General Hydrogen and CTFCA. BOC took the responsibility for system integration, system safety analysis and installation. Together with NRC and General Hydrogen, they are developing a quality assurance program for hydrogen fuel.

A number of factors influenced the design of the station; one of the most significant factors was that NRC-IFC was relocated to a new site in the summer of 2006. Another factor was that the hydrogen load was uncertain. Therefore, the station was designed to be scalable. Furthermore, the partners had a number of options they wanted to explore including 700 bar fueling capabilities and remote monitoring capabilities.

The original design concept was to generate hydrogen on site via water electrolysis. However, the NRC-owned electrolyzer was a 1999 design and required costly upgrades to meet the 2004 fuel quality requirement of the VFCVP. An electrolyzer designed for the new specifications is being investigated for the new station. In the meanwhile gaseous hydrogen is being delivered in tube trailers. This hydrogen is recovered from an industrial plant and is therefore considered renewable.
Figure 65 Photos of the hydrogen compression and storage system (left) and dispenser system installed at the Pacific Spirit Station, Vancouver.

Figure 66 Flow diagram of Pacific Spirit Station in Vancouver.
13.2 Site visit and workshop in Vancouver on 7 March 2006

On 7 March 2006 the Annex 18 group visited the Institute for Fuel Cell Innovation, National Research Council, in Vancouver. A workshop with key project partners and a site visit to the Pacific Spirit Station was arranged.

The workshop included presentations by Lori Law, the overall project manager from the National Research Council (NRC), Andre Lanz from General Hydrogen, who is responsible for the storage tower and dispenser, and Bob Boyd from BOC. BOC is the station integrator and provider of the compression system.

Some of the issues that came up in the discussions with the Annex 18 group were:
- Purity of hydrogen, especially when produced on site
- Quality assurance approach
- Consistency from station to station
- Approaches to providing high pressure hydrogen to the vehicle; cascade versus boost storage and compression
- Filling approaches / sensor options at the dispenser: wired, wireless, direct
- Billing processes
- Bulk storage tanks / cycling / risk assessment
- On-board storage tanks (composites not currently allowed in US because there is no ASME code)

One major item of the discussion, both with respect to the Vancouver station, but also in general, is the difficulty of measuring the energy requirement for a hydrogen compressor. Manufacturers do not routinely know this parameter or measure it precisely, and steady state modeling and analysis underestimates the energy consumption.

After the workshop discussion, the participants viewed the station area located on the grounds of NRC-IFC. The compressor, storage, and dispensing components were on view. Permitting for the facility was done with the local authorities, but because the hydrogen facility was located on the Institute’s property and not open to the public, the process was not extensive.

13.3 System Design and Operation

The compression and low pressure storage system supplied by BOC (Figure 66) includes two diaphragm compressors. The first stage compressor was matched to on-site production capabilities and can run continuously with the presence of a hydrogen generator (e.g., electrolyzer). This first stage compressor can under normal operation compress 29 kg of hydrogen per day to approximately 90 bar. The second compressor boosts the pressure from the first bank at 90 bar to 250 bar, which is the operating pressure of the second and third banks. The second compressor is also used to increase the hydrogen pressure from 250 bar to 450 bar. Having intermediate storage allows the 450 bar storage tower to be topped up without having to start up the generator or take hydrogen from the tube trailers.

The 450 bar storage and dispensing was supplied by General Hydrogen and integrated into the station by BOC. The 450 bar storage consists of three separate banks and stores up to 67 kg of hydrogen in an enclosure with a footprint of 1.8 m by 2.4 m. When one of the banks gets below 90% a fuel request triggers the hydrogen supply system. Depleted banks are filled from highest to lowest bank.
The dispenser and high pressure storage feature industrial design qualities for use at a public site. The storage and dispensing can be upgraded to 700 bar by changing some components. The design would not be affected.

There are three fueling modes associated with this dispenser:

- **Wired:** This adopts the California Fuel Cell Partnership (CaFCP) fueling protocol (version 7) and allows for the transfer of temperature and pressure data from the vehicle to the dispenser. Data transfer occurs by way of a connector.

- **Wireless:** This adopts the draft SAE J2601 fueling protocol and allows for the transfer of temperature and pressure data from the vehicle to the dispenser. Data transfer occurs by way of infrared signals.

- **Direct:** This adopts the CaFCP non-communication algorithm without any data transfer from the vehicle to the dispenser.

The Ford fuel cell vehicles use the wired fueling method. The General Hydrogen dispenser is capable of supplying hydrogen to a diverse fleet with programmed features such as registering vehicle identification, date, time, mass dispensed, and also has the capability for future pay at the pump transactions.

In addition to supplying the compression and storage installation, BOC supplied engineering, construction, and commissioning services. The NRC provided intelligent controls, facilities integration, and remote monitoring of the system. Dynatech Industries Ltd composite vessels are being used for ground storage. The compressors and low pressure storage is skid mounted on an existing hydrogen tube trailer storage pad to allow for relocation and to minimize cost.

The total amount of hydrogen dispensed during a one-year period (April 1, 2005 through March 31, 2006) was approximately 900 kg. This includes dispenser testing and refueling quantities from vehicles prior to service.

The dispenser has performed very well and a consistent fill for the cars has been reached. The average fill per car is approximately 4 kg of hydrogen. The Ford fuel cell vehicles have been in service for one year as of March 31st 2006. The fleet of the five cars running in Vancouver and Victoria have traveled approximately 35,000 km and are meeting performance expectations.

Permitting for the site was probably easier than for other stations because the NRC-IFC had previously completed its Environmental Assessment, granting site approval from the regulatory agency of the university as part of a larger project to upgrade its laboratories. The facility is federally regulated because it is a federal institution. However a number of permits were still required to ensure the station was operational. These included a development permit, a project concept approval, a HAZOP and site safety review, a pressure vessel inspection, an electrical installation inspection, a license to occupy, and a service agreement.

Overall the station has functioned well; it is fully operational and has an excellent safety record. There has also been excellent cooperation and support from BOC and General Hydrogen on integration of the BOC designed compression skid and the existing General Hydrogen Equipment. A comprehensive safety review was completed and included representatives from funding partners and the local public safety authorities and a third party safety expert.
13.4 Conclusions & Recommendations

The overall goal of the Pacific Spirit Station (PSS) in Vancouver is to demonstrate a flexible hydrogen refueling station using advanced compression and storage systems suitable for several hydrogen sources and users [6].

The original objective with the Annex 18 evaluation of the hydrogen station in Vancouver was to evaluate the overall compressor and storage system design, gather detailed compressor data, model the compression and storage system installed at Pacific Spirit Station, and integrate this into the hydrogen station simulator described above (Figure 45). This was not possible to achieve within Phase I of Annex 18 due to lack of operational data. The low level of operation was caused by a shortage of personnel and the relocation of the station in 2006.

After the relocation of the system, a full data stream from all components of the station is expected. A new electrolyzer is being considered installed at the Pacific Spirit Station. It is recommended that this is modeled in Phase 2 of Annex 18, using the IEA hydrogen station simulator described above (Figure 45).

The recommendation for future work is to calibrate the empirical coefficients for the hydrogen compressor model based on actual data collected, complete the overall compressor system model, and simulate various hydrogen refueling regimes and scenarios based on a real demand profile.

The outcome of the such a modeling effort would be conclusions on the flexibility of the technical configuration chosen at Pacific Spirit Station. Also, the verification of a more detailed compressor model would be a great improvement to the existing hydrogen refueling station model.
14 Conclusions and Recommendations

14.1 Metal Hydride-based Hydrogen Storage Systems

Thermally coupled electrolyzer/metal hydride/fuel cell systems for stationary applications can have a high overall energy system efficiency. A system simulation model suitable for parametric studies and optimization of design and controls of integrated metal hydride hydrogen systems have been developed, based on actual data from a demonstration system in Japan.

Detailed system simulations show how the electrolyzer, metal hydride, and fuel cell can be thermally coupled and operated together if sized properly. The simulations also illustrate the importance of a thermal coupling between the metal hydride hydrogen storage and the fuel cell. A control strategy that regulates the water flow through the metal hydride, and thereby ensures that the hydrogen gas pressure in the storage is sufficiently high, was demonstrated and evaluated.

14.2 Integrated Renewable Energy Hydrogen Systems

A strategic approach was adopted to the modeling and analysis of the integrated renewable energy hydrogen systems, namely the HARI-system in the UK. Due to the lack of data for some key components the analysis focused on optimization of system performance rather than looking at very detailed aspects of technical performance.

The conclusions and recommendations from the analyses performed can be summarized by the following:

- A general hydrogen systems optimization methodology suitable for both the TRNSYS and HOMER software tools was developed.
- There is an good agreement of results when this methodology is applied to both the HOMER and TRNSYS when modeling the HARI systems.
- General system optimization based on cost using HOMER or TRNSYS shows that it is possible to significantly reduce the size of some of the key system components of the HARI system, particularly the electrolyzer, hydrogen storage, and the CHP-unit, without compromising system performance.
- There is a significant difference in system operation observed in HOMER and TRNSYS due to different control strategies; however the end results are very similar.
- Achieving true optimum performance of this type of integrated renewable energy hydrogen system requires that both the physical components and control strategy deployed are analyzed and optimized in an integrated manner.
- Further modeling work on integrated renewable energy hydrogen systems should involve more effort to accurately characterize the specific system controller.
14.3 Electrolyzer-based Hydrogen Fueling Stations

Three hydrogen stations (Reykjavik, Malmö, and Vancouver) have been evaluated, in more or less detail. The various analyses show that there are four (4) key system design parameters for an electrolyzer-based hydrogen refueling station:

1. Electrolyzer operating pressure
2. Compressor operating pressures
3. Hydrogen storage capacity (dependent on pressure and volume)
4. Hydrogen demand (including pressures and flow rates)

The operating pressures in commercially available electrolyzers are typically in the range 1-15 bar, depending on the technology selected (non-commercial high-pressure 30 bar electrolyzers are under development). This means that there is a need to compress hydrogen, first into stationary storage tanks at the fueling station (typically 200 bar), and later (via dispensers) into storage tanks onboard vehicles (typically 350 bar). A closer look at the four key system design parameters listed above clearly illustrate that there should exist some kind of optimal hydrogen compression and storage system configuration (with respect to pressure).

One attractive design is a multistage compressor and storage system that, for example, first takes hydrogen produced by the electrolyzer at 10 bar and compresses it into an intermediate storage tank up to 100 bar before a second stage compressor takes it further up to 250 bar in a secondary storage, or up to 450 bar in the dispenser system. This seems to be a flexible design with several operational advantages because:

- The electrolyzer can operate independently of the hydrogen dispenser, and vice versa
- A multi-pressure level system allow for more efficient filling (high pressure gas only used on demand)
- A large part of the total hydrogen storage capacity can be used (due to boost compressor)

Another approach is to design the hydrogen fueling stations so that they better balance the hydrogen produced by the electrolyzer with the hydrogen demand at the dispenser. This is best done using electrolyzers that are capable of running efficiently at part-load for long periods of time. The increased electrolyzer run-time should lead to a higher overall electrolyzer system efficiency, due to more efficient use of system components in the balance of plant, some of which are running almost 100% of the time anyway.
14.4 General Conclusions

System Evaluations:
- Five (5) demonstrations were modeled and analyzed in detail.
- Three (3) demonstrations were analyzed in less detail.
- Eight (8) demonstrations were discussed in separate case studies; three (3) of these were also looked at in more detail.
- Proper validation of data, detailed modeling and system analysis is a tedious process; a minimum of two person-years should be allowed in each detailed evaluation.

Data Monitoring:
- More extensive monitoring of systems is required; project developers must be made aware of how important this is and should be given a list of parameters to measure.
- It is difficult to measure hydrogen flow in compressors, as these are dependent on temperature and pressure.
- Energy measurements and validated models for hydrogen compressors are needed for benchmarking of the technology.

Modeling Tools:
- Optimal design and operation of integrated hydrogen systems can only be found on a case-by-case basis; validated modeling tools are needed.
- The development of generic hydrogen energy models (e.g. HYDROGEMS) should be continued, and made available for several system simulation platforms (e.g., TRNSYS, EES, MATLAB).

System Design:
- Thermally coupled electrolyzer/metal hydride/fuel cell systems for stationary applications can have a high overall energy system efficiency, up to 45-50%.
- Demonstration systems are often over-sized; this is particularly true for electrolyzer-based hydrogen fueling stations.
- The efficiency of electrolyzer systems can be improved by 10-15% with new and more innovative balance of plants and operational schemes.

Controls Systems:
- Control system models need to be handcrafted for each specific system configuration.
- Demonstrations system can provide a test-bed for testing of control algorithms, as in the FIRST and HARI projects.

Cost-Benefit Analyses:
- Hydrogen component cost-functions (e.g., data bases at Sandia National Laboratory, USA and IFE, Norway) should be updated.
- Cost functions including replacements due to limited life, commissioning, O&M costs etc. should be coupled to technical models.
14.5 Recommendations for Phase 2 of Annex 18

Phase 2 of Annex 18 was approved by the Hydrogen Implementing Agreement Executive Committee in November 2006. The Task will operate from January 2007 through December 2009. Subtask B will continue with the ongoing objective to model and analyze integrated hydrogen demonstration systems.

The first activity in Phase 2 will be modeling of the Italian hydrogen house, with a focus on control strategies and system performance. Another priority is gathering data on compressor operations to improve compressor modeling. Yet another priority will be including a reformer-based project in the portfolio. Finally, the group will work to continue comparisons between similar systems for the purpose of trend analysis and lessons learned.

Specific Recommended future work in Phase 2 of Annex 18:

- Perform three (3) new detailed technical evaluations (fill voids in renewable energy and natural gas system matrix).
- Develop new models for CHP-systems, hydrogen compressors, and generic controllers.
- Set up simulations so that they are more suitable for techno-economic system optimization.
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References


