Tool for Optimal Design and Operation of Hydrogen Storage Based Autonomous Energy Systems

B. Oberschachtsiek, D. Lemken, M. Stark, G. Krost

This document appeared in

Detlef Stolten, Thomas Grube (Eds.):
18th World Hydrogen Energy Conference 2010 - WHEC 2010
Parallel Sessions Book 5: Strategic Analyses / Safety Issues / Existing and Emerging Markets
Proceedings of the WHEC, May 16.-21. 2010, Essen
Schriften des Forschungszentrums Jülich / Energy & Environment, Vol. 78-5
Institute of Energy Research - Fuel Cells (IEF-3)
Forschungszentrum Jülich GmbH, Zentralbibliothek, Verlag, 2010
ISBN: 978-3-89336-655-2

Tool for Optimal Design and Operation of Hydrogen Storage Based Autonomous Energy Systems

B. Oberschachtsiek, D. Lemken, ZBT- Duisburg, Germany
M. Stark, G. Krost, University Duisburg-Essen, Germany

Abstract

Decentralized small scale electricity generation based on renewable energy sources usually necessitates decoupling of volatile power generation and consumption by means of energy storage. Hydrogen has proven as an eligible storage medium for mid- and long-term range, which – when indicated – can be reasonably complemented by accumulator short term storage. The selection of appropriate system components – sources, storage devices and the appertaining peripherals – is a demanding task which affords a high degree of freedom but, on the other hand, has to account for various operational dependencies and restrictions of system components, as well as for conduct of load and generation.

An innovative tool facilitates the configuration and dimensioning of renewable energy based power supply systems with hydrogen storage paths, and allows for applying appropriate operation strategies. This tool accounts for the characteristics and performances of relevant power sources, loads, and types of energy storage, and also regards safety rules the energy system has to comply with. In particular, the tool is addressing small, detached and autonomous supply systems.

1 Introduction

Small autonomous energy supply systems based on renewables such as solar and wind power can significantly contribute for saving fossil energy resources as well as for CO_2 emission reduction; on the other hand, heavy fluctuations caused by solar day/night cycles and/or weather dependent irradiation as well as wind volatility complicate proper and continuous operation. According to the particular load demand, this implies the necessity to provide short and/or long term energy storage. The selection of appropriate storage types and sizes finally depends on the renewable energy source chosen, the expected energy harvest profile, as well as load demand characteristics.

Various principal configurations are supposable for autonomous, decentralized and renewables based systems for the electric supply of, for instance,

- remotely located telecommunication base stations (up to 2.5 kW) [1], [2];
- solitary buildings such as alpine huts, summer residences or small farms (up to 5 kW) [3], [4];
- farms and small settlements in developing countries (above 5 kW) [5].

To assure effectiveness in practical operation, appropriate selection and dimensioning of the particular components is indispensable. This requires collection of comprehensive knowledge and experience from various domains such as electrical, process and chemical engineering, and is therefore a complex and time consuming task.

A tool being able to prudently and flexibly master this task is currently under development and will be presented in the following; such tool must rely on the knowledge of above mentioned domains, comprising the characteristics and specifics of available system components, their applicable variants (e.g., pressurized vs. metal-hydride hydrogen storage), and must consider the operational interactions and restrictions between all system components involved. The tool conducts the system design in the following steps:

1. constitution of system architecture under energetic and economic aspects;
2. dimensioning of components by operative simulation of the complete system;
3. development of an appropriate operation strategy for the complete system.

An expert system was chosen for task a) of components selection as it provides transparent and clearly arranged set-up of rules, weighting of input information and inferences, as well as an explanation capability; it is described in more detail in [6].

Task b) demands simulation of the entire plant under consideration of realistic load and (renewables based) generation profiles for longer periods of time with at the same time sufficient temporal resolution in order to comply with daily load and generation fluctuations; an appropriate simulation package comprising models of various plant components was presented in [7]; several of these models are applied here, too. Rather, the operational behavior of metal hydride storage embedded within a hydrogen path has yet to be modeled according to the results of measurements as briefly sketched below in section 5 and more extendedly described in [8].

Finally, an equitable operation strategy c) is required which cares for reliable, un-interrupted supply under smooth commitment of devices in order to maximize their lifetime expectancy and minimize operation cost.

This design tool will be sketched in the following; the functional part a) was finalized most recently while parts b) and c) are under present development. After completion the tool will be a significant contribution to the launch of small hydrogen storage based energy systems.

2 Power Supply Structure

The main components, which self-sustaining renewable energy based electricity supply systems typically consist of, can be seen in Fig. 1. Types of renewable energy sources (solar/wind) usually are disposed according to local conditions (given irradiation/wind profiles, space for allocation etc.), as well as given load shapes/cycles. Small wind generators are available on the market, and photovoltaic (PV) panels can be individually composed to arbitrary peak power output.

Coincidence of sources and load profiles further determines existence and intent of storage types, used in particular for short term (day/night cycles) and/or mid-/long-term (weather periods, seasons) time range. While accumulators (conventionally usually lead-acid or NiMH but increasingly lithium-ion types) are well suited for short term storage, hydrogen has proven well as a reasonable mid-/long-term storage medium in consequence of low storage losses [9], [10].

For hydrogen production electrolyzers [11] with appropriate ratings are available; in case of pressurized hydrogen gas storage, high pressure electrolyzer types save separate compression effort. On the other hand, as another promising technology metal-hydride beds provide easy and safe hydrogen storage. Such metal-hydride storages allow a higher energy density than pressurized gas storages, which reduces the required space, and provide intrinsic safety by “freezing” in case of leakage [12], [13].

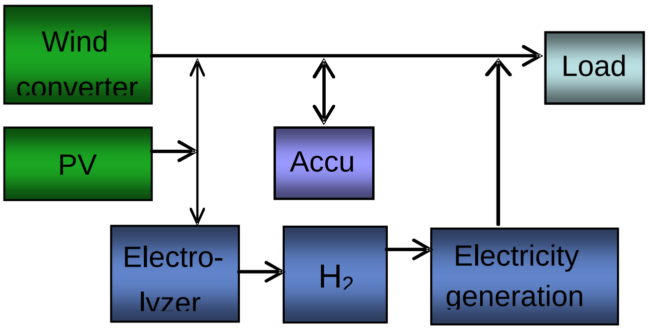

Figure 1: Self-sufficient electrical power supply structure.

The re-conversion of hydrogen to electricity can be achieved by either small gas-engine driven generators, or fuel cells [14], which both are available in relevant ratings. In general, but especially in the latter case, cost considerations play a weighty role if commercial and not pilot systems are considered. Table 1 taken from [2] gives an exemplary survey of various self-sustaining telecommunication base supply systems with typical loads ranging from some tens of W up to 2.3 kW.

Table 1: Self-sustaining renewable energy based telecommunication hub supply approaches [2].

Application	Site power required	Example solar and wind solution
GSM Base Station 2/2/2	600 - 1800 W	4 kW Solar Array and 6 kW turbine depending upon conditions
GSM Base Station 4/4/4	900 - 2300 W	6 kW Solar Array and 6 kW turbine depending upon conditions
UMTS Node B Macro/Fiber - 2/2/2	750 - 1000 W	3 kW Solar Array and 2.5 kW turbine depending upon conditions
UMTS Node B Macro/Fiber - 4/4/4	1300 – 1700 W	4 kW Solar Array and 2.5 kW turbine depending upon conditions
Large WiMax Base Station	1.3 kW (4 Sector)	4 kW Solar Array and 2.5 kW or 6 kW turbine depending upon conditions
Metro WiFi	<30 W includes a back-haul solution	100 W Solar Array and small turbine depending upon conditions
P2P link (two heads)	110 W for two units	1 kW Solar Array and 600 W or 2.5 kW turbine depending upon conditions

3 Expert System Based Components Selection

An expert system was chosen for the task of components selection, because it provides clearly arranged knowledge input in form of rules, weighting of choice factors, as well as transparency in reasoning by an explanation subsystem. The multitude of implemented rules (581 in total) results from the detail grade of parameters considered, such as:

- Local generation conditions:
  - *expected yearly wind/solar energy harvest*: the particular source is only favored if certain site-specific parameters exceed a given threshold value (e.g. 900 kWh/a per m^2 for solar irradiation or 3 m/s average wind speed); special aspects such as shadowing of photovoltaic modules or slipstream of wind turbines are also regarded;
  - *available area*: the particular source is only considered if the available plant area (for, e.g., photovoltaic modules surface) admits harvest of global yearly energy demand;
  - *quality of solar radiation:* diffuse or direct radiation require different types of photovoltaic panels (amorphous vs. mono-crystalline);
  - *installation circumstances:* selection of system components depending on building restrictions such as height of plant, etc.
- Qualitative load conditions:
  - *cyclicity of load profile*: co-incidence/adversity of load forecast and energy harvest expectation (e.g., load peaks during daytime give favor for photovoltaic approach);
  - *volatility* of load: heavy and rapid discrepancies between load maxima and minima substantiate the necessity of short term storage.
- Storage conditions:
  - *hydrogen path*: needed for compensation of solar seasons-based cyclicity (long term) [15], or for bridging calm wind periods (mid-term);
  - *accumulator*: required for solar day-night cycle and/or fast power peak compensation (short term).
- Storage technology:
  - *hydrogen path*: metal hydride vs. pressurized gas,
  - *accumulator*: lead-acid, lithium-ion or NiMH,
  - according to, e.g., economical and innovation aspects. For hydrogen storage, the type of electrolyzer is selected under consideration of the H_2 pressure required by the actual storage technology.
- Electricity generation from hydrogen:
  - the *relevant component* (gas engine driven generator, fuel cell) is determined under global consideration of the existing load conditions.
- Component specific conditions:
  - *operative restrictions* such as minimal operation time, minimal/maximal loading of certain devices etc.;

- o *safety rules* demanding restrictions in use of hydrogen.
- Economic considerations:
  - o enlargement of basal physical expert system rules by *economic aspects* (e.g., less expensive amorphous photovoltaic cells if module surface area admits).
- Innovation considerations:
  - o possible release for choosing *innovative system components* if available; in this case, costs are of second range.
- Comparison with preliminary selection by operator:
  - o a *preferred set of components* selected by the user in advance can be regarded and compared to the expert solution by hindsight.

The implementation was made by use of the freely available shell "KnowMe" [16]. The expert system was tested with multiple autonomous power supply requirements ranging from simple telecommunication bases up to rural settlements in extreme climatic zones. In all cases the suggestions have proven as plausible and useful; several examples are given in [6]. In Fig. 2 an example of the explanation surface is given, reasoning the application of a certain rule and weighting.

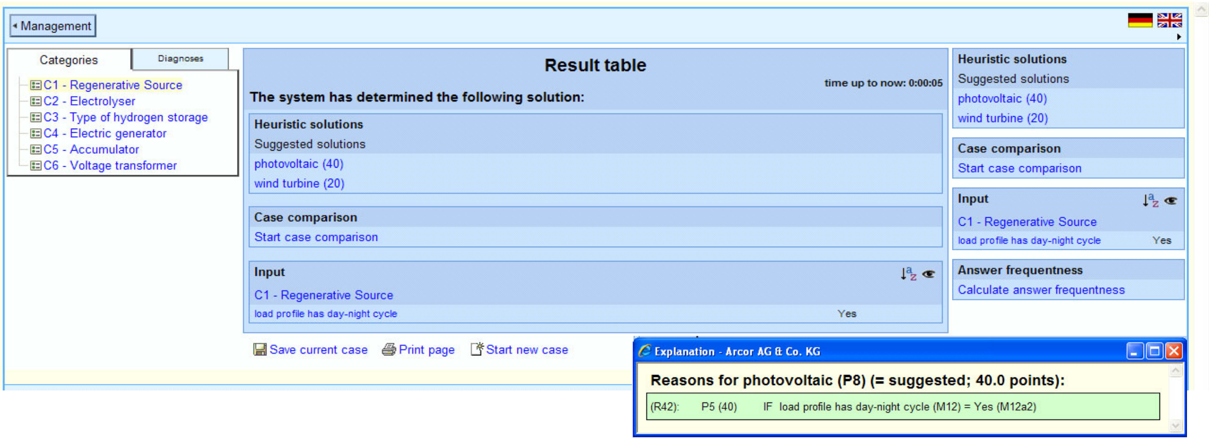

Figure 2: Explanation functionality displaying the corresponding rule(s) and weighting(s).

4 Dimensioning of Components and Regard of Operative Conditions

After selection of components their sound rating is the logical next step. The realized concept provides a library of individual modular component blocks based on Matlab/Simulink® models of

- stochastically operated primary sources (photovoltaic and wind generation, both of different types),
- electrolyzers of different types (including high pressure electrolyzers),
- long and short term storage systems (e.g. variants of hydrogen storage, various accumulator types),
- conversion of stored hydrogen to electricity (fuel cells and small gas engine driven gen-sets)

from which the particular complete energy systems can be individually composed according to the results of the components selection. For proper dimensioning, operation of the complete plant with given load and wind/solar generation profiles has to be simulated and optimized over longer periods of time – usually a complete year for rating of seasonal storage – at sufficient temporal resolution (typically 15 min) in order to widely cover power peaks and short term storage requirements. This part is presently under development and will largely be relying on component models which were successfully applied for multi-criterial optimization of micro CHP home plant operation [17]. The task considered here is of minor complexity, nevertheless the operational restrictions such as minimal run time of components or maximal number of operation cycles per day etcetera have also to be considered; the optimization process itself which can be arbitrarily oriented to technical, energetic or economic aspects is comprehensively described in [18].

5 Measurements as Basis of Metal Hydride Storage Modeling

In particular, for hydrogen storage different principles are applicable: liquid (of less importance for the demands considered here), pressurized gas or metal hydride. Especially for the latter relevant data for exact modeling are not yet available. Therefore, comprehensive and systematic measurements are currently conducted, the results of which will complement the corresponding simulation model.

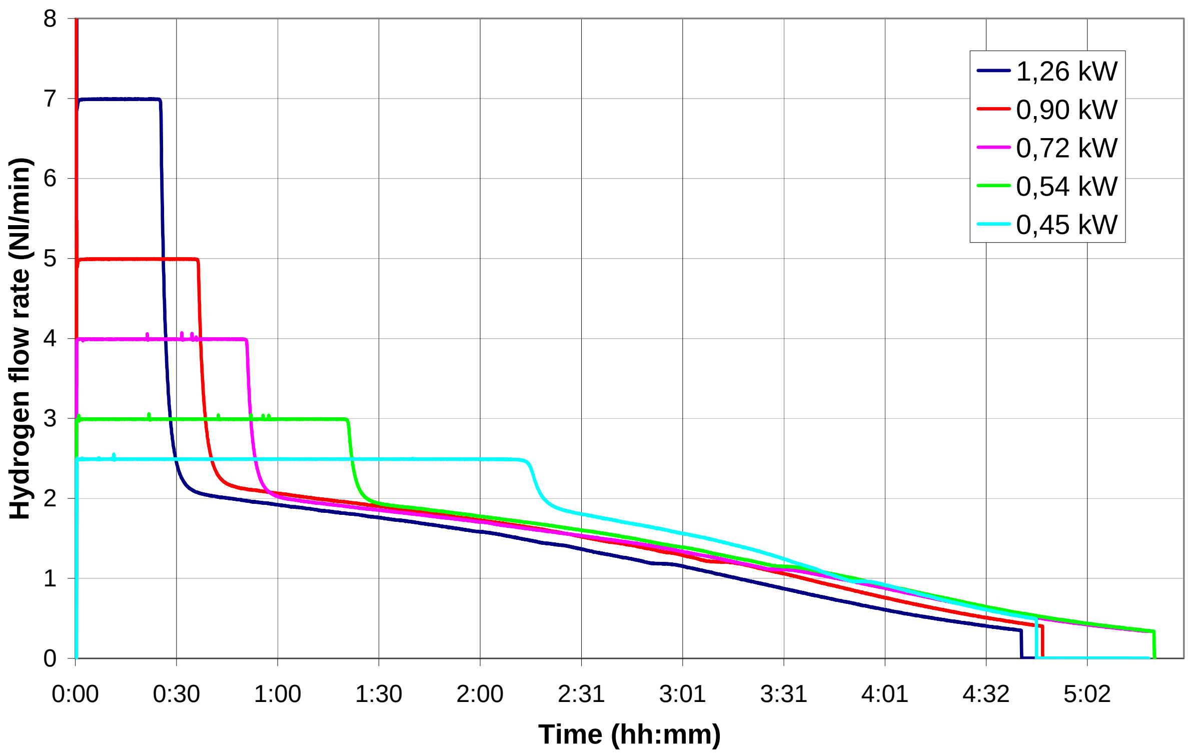

Figure 3: Desorption curves for different hydrogen flow rates at ambient temperature of 25 °C.

Two very similar metal hydride storage tanks, which are designed for a reversible hydrogen capacity of about 60 g, have been tested so far. Typical desorption curves of such a tank are shown in Fig. 3. Different set points of the hydrogen flow rate were adjusted at an ambient temperature of 25 °C. The maximum duration of constant flow rates varies from less than 30 minutes for an adjusted flow rate of 7 Nl/min to more than 2 hours for 2.5 Nl/min. It can be seen that by using only one tank a constant hydrogen flow of 5 Nl/min (equivalent to 0.9 kW_{th}) can be provided for about 37 minutes. With two tanks operated in parallel the constant delivery time can not only be doubled but be expanded by a factor of 3.6 up to 134 min. Another important influencing factor on the duration of a required hydrogen flow is the ambient temperature of the tested tank. As seen in Fig. 4a, the duration of constant hydrogen flow of 5 Nl/min increases nearly one minute per one Kelvin of higher temperature for the tested tanks. Especially in self-sufficient energy systems, where hydrogen storages will not always be filled to maximum, the fill level of the tank has to be considered. As shown in Fig. 4b the lower the fill level is when starting the desorption, the shorter is the operation time for a constant flow (here 5 Nl/min).

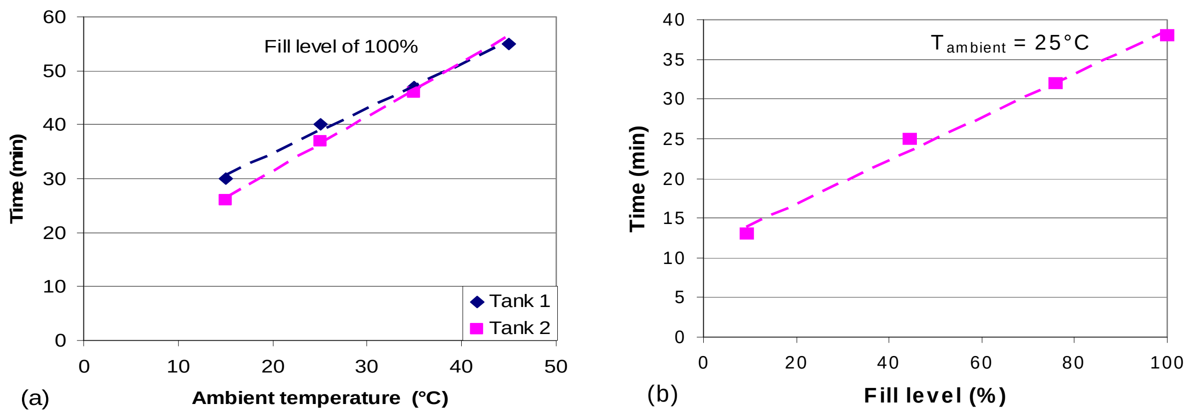

Figure 4: Influence of ambient temperature (a) and fill level of tank (b) on duration of constant flow rate of 5 Nl/min.

The next steps will be to obtain relevant data for the charging process such as filling duration and fill level as function of pressure, hydrogen flow rate and temperature. Additionally dynamic test cycles will be performed. The metal hydride storage will be alternately filled and discharged within different time periods from several minutes to hours resulting in different fill levels. So limits of minimum/maximum duration for loading and unloading will be determined. Finally the electrolyzer, metal hydride storage tanks and the fuel cell system will be operated together. At this an investigation of the interaction of the system components is enabled as well as the optimization of operation parameters. Thus, the verification of the simulation of the hydrogen storage path can be performed.

6 Conclusion and Outlook

Self-sustained, detached and renewables based electricity supply implicitly requires storage of energy. Even if such systems usually are small with regard to installed power, the multitude of applicable components as well as of constructive, operative, and safety related constraints provokes eligibility of technical assistance in plant design. A comprehensive tool for proper composition, dimensioning and operation of autarkic electricity supply is under development and was briefly sketched. The complete three-step tool will result in

- helping manufacturers of electrolyzers, hydrogen storages and fuel cells to develop concerted building blocks of particular devices which can individually and easily be combined to complete energy systems;
- facilitating the design of self-sustaining energy systems with reasonable operational performance;
- contributing to the development of new application areas of renewable energies;
- supporting the launch of fuel cell technology by easing engineering of the hydrogen path at reduced cost.

Acknowldegement

Thanks to “Verein für Energie und Umwelttechnik e.V.“ for sponsoring this project (15863 N) with allocated funds from “Bundesministerium für Wirtschaft und Technologie (BMWi)“ through „Arbeitsgemeinschaft industrieller Forschungsvereinigungen "Otto-von-Guericke" e.V. (AiF)“.

References

[1] N.N., Sustainable energy use in mobile communication, Ericsson AB, 2007.

[2] N.N., Solutions Paper: Alternative power for mobile telephony base solutions, Motorola Inc., 2007.

[3] P. Hollmuller, J. Joubert, B. Lachal, K. Yvon, Evaluation of a 5 kw_p photovoltaic hydrogen production and storage installation for a residential home in Switzerland, Int J Hydrogen Energy 25, 2000.

[4] K. Voss, A. Goetzberger, G. Bopp, A. Haeberle, A. Heinzel, A. Lehmberg, The self-sufficient solar house in Freiburg – results of 3 years of operation, Solar Energy, 58,1996.

[5] S. Busquet, F. Domain, R. Metkemeijer, D. Mayer, Stand alone power system coupling a PV field and a fuel cell description of the selected system and advantages, Proceedings of the PV in Europe conference, Roma, Italy, 2002.

[6] M. Stark, M. Hausmann, G. Krost, Expert System for Component Selection of Decentralized Self-sufficient and Regenerative Electricity Supply Systems, Proc. of “Intelligent Systems Application to Power Systems (ISAP) 2009”, Curitiba (Brazil), November 2009.

[7] J. Matics, G. Krost, Intelligent Design of PV Based Home Supply Using a Versatile Simulation Tool, Proc. of “Intelligent Systems Application to Power Systems (ISAP) 2005”, Arlington, Virginia (USA), November 2005.

[8] D. Lemken, M. Stark, B. Oberschachtsiek, G. Krost, Self-sufficient and Regenerative Electricity Supply Systems with Hydrogen Based Energy Storage, Conference on Control Methodologies and Technology for Energy Efficiency (CMTEE) 2010, Vilamoura (Portugal), 2010.

[9] P.A. Lehman, C.E. Chamberlin, G. Pauletto, M.A. Rocheleau, Operating experience with a photovoltaic-hydrogen energy system, Int J Hydrogen Energy, 22, 1997.

[10] T. Nakken, L.R. Strand, E. Frantzen, R. Rohden, P.O. Eide, The Utsira wind-hydrogen system – operational experience, EWEC, European Wind Energy Conference, 2006.

[11] B. Paul, J. Andrews, Optimal coupling of PV arrays to PEM electrolysers in solar-hydrogen systems for remote area power supply, Int J Hydrogen Energy, 33, 2008.

[12] E.S. Kikkinides, M.C. Georgiadis, A.K. Stubos, On the optimization of hydrogen storage in metal hydride beds, Int J. Hydrogen Energy, 31, 2006.

[13] B.D. MacDonald, A.M. Rowe, Experimental and numerical analysis of dynamic metal hydride hydrogen storage systems, Journal of Power Sources, 174, 2007.

[14] D. Shapiro, J. Duffy, M. Kimble, M. Pien, Solar-powered regenerative PEM electrolyser/ fuel cell system, Solar Energy, 79(5), 2005.

[15] J.P. Vanhanen, P.D. Lund, J.S. Tolonen, Electrolyser-metal hydride-fuel cell system for seasonal energy storage, Int J Hydrogen Energy, 23, 1998.

[16] KnowMe: http://www.d3web.de

[17] J. Matics, G. Krost, S. Freinatis, G. Dubielzig, Adaptive and Flexible Energy Management for Micro Combined Heat and Power Systems, Proc. of IASTED International Conference on “Power and Energy Systems”, Clearwater, Florida (USA), Jan. 2007.

[18] J. Matics, G. Krost, Micro Combined Heat and Power Home Supply: Prospective and Adaptive Management Achieved by Computational Intelligence Techniques, Applied Thermal Engineering 28, 2008, pp. 2055-2061.