Expert System for Component Selection of Self-sufficient and Regenerative Electricity Supply Systems with Hydrogen Storage

Maike Stark, Matthias Hausmann & Gerhard Krost, *IEEE*
El. Power Systems Institute
University of Duisburg-Essen
Duisburg, Germany
maike.stark@uni-due.de

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.**

This paper delineates a most recently developed part of a design tool where the primary selection of system components is based on an expert system which takes into account the characteristics and performance of relevant renewable power sources, load shapes, storage systems and safety rules, and also covers economic as well as ecological aspects. In particular it allows for optimal, comprehensible and transparent selection of appropriate power supply components for applications such as telecommunication relay stations, residential buildings or farms in remote rural areas.

Accumulator, Component Selection, Decentralized Power Supply, Expert System, Hydrogen Storage, Photovoltaic, Renewable Energy

I. 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 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 still missing; 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 the operational interactions and restrictions between all system components involved.

In the frame of a current research project such tool is under development. It provides three successive steps of plant layout:

- expert system based selection of components;
- numerical simulation based dimensioning of devices;
- simulation based derivation of appropriate operation strategy.

In the following the initial part-system of the design tool, the expert system based components selection which has been elaborated most recently, will be reported. In particular an expert system was chosen for this task as it provides transparent and clearly arranged set-up of rules, weighting of input information and inferences, as well as an explanation capability.

II. Power Supply Structure

The principal components, which self-sustaining renewable energy based electricity supply systems typically consist of, can be seen in Fig. 1.

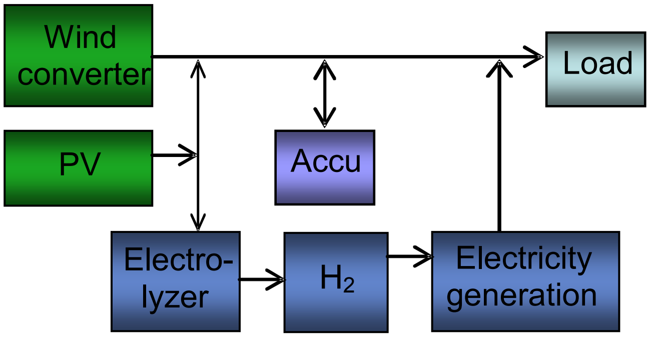


Fig. 1. Self-sufficient electrical power supply structure.

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 [6], [7].

For hydrogen production electrolyzers [8] 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 requisite space, and provide intrinsic safety by "freezing" in case of leakage [9], [10].

The re-conversion of hydrogen to electricity can be achieved by either small gas-engine driven generators, or fuel cells [11], 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.

III. Component Selection Criteria as Knowledge Base Contents

In order to be incorporated into the expert system's rule base, the selection criteria for the electricity supply system components had to be carefully analyzed and ordered. The following first-level criteria categories were identified:

TABLE I
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 backhaul 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

- 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) [12], 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.;
  - *safety rules* demanding restrictions in use of hydrogen.
- Economic considerations:
  - enlargement of basal physical expert system rules by *economic aspects* (e.g., less expensive amorphous photovoltaic cells if module surface area admits).
- Innovation considerations:
  - possible release for choosing *innovative system components* if available; in this case, costs are of second range.
- Comparison with preliminary human selection:
  - a *preferred set of components* selected by the user in advance can be regarded and compared to the expert solution by hindsight.

IV. Expert System Tool and Knowledge Implementation

As mentioned above, an expert system was chosen for the principal component selection task due to its openness in structuring logical decision coherences, plain expandability, uncomplicated confinement and its transparency given by an explanation sub-system. The latter is not only a beneficial property for the user who can catch up comprehensively on the system's reasoning; rather it also has proven as an estimable means to check the consistency of the expert system's rule base by systematically asking for the decision coherences during rule-base implementation.

While for various former expert system projects an own special inference engine development was used, in this case the PC based expert system tool KnowMe [13] was applied; this tool is freely available on the internet and provides a graphical environment for the development of knowledge based systems, supporting the following knowledge types:

- rules, entered by special editors for decision trees or decision tables;
- cases, entered under regard of weighting, abnormities and partial similarities;
- overlapping relations, entered in form of tables.

The tool is rather easy to handle and provides interfaces to the MS-office world, and also allows for subordination of algorithmic calculations. The knowledge base was set up by entering rules treating the component selection criteria outlined above in section III., using relevant

- KnowMe rule codes
- weightings
- correlated rules
- references
- possible answers
- types of rules (e.g., relation to numerical values or multiple choice questions in EXCEL).

The resulting knowledge base is saved under MS-office in order to allow later modifications of the expert system rules, if required, as well as to provide proper documentation and sufficient comprehension.

V. Example Cases

To outline the principal proceeding of the component selection expert system, the following example cases are considered:

A. Remote Summer Residences:

An ensemble of three single family summer residences, remotely located in the German mountains and therefore not connected to the public grid, should be electrically supplied by means of renewable energies. The typical electric load profile of the three summer houses over one week is shown in Fig. 2.

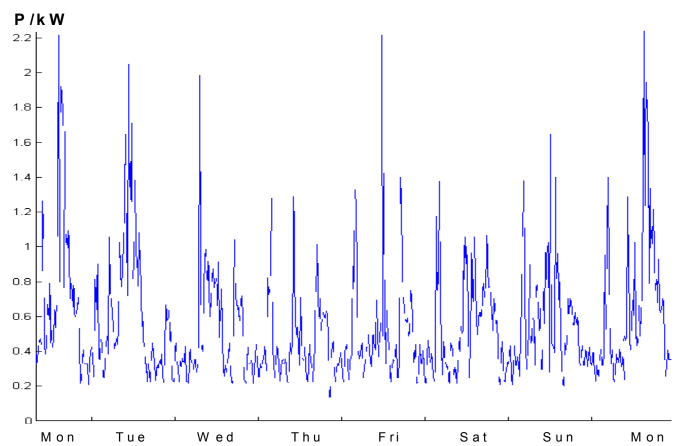


Fig. 2. Electrical load profile of three summer residences.

The roofs of the houses have viable alignment to south direction, and the estate would allow for placement of a wind generator. Regarding expected renewable energy harvest, a 1 kW_{peak} south-oriented photovoltaic panel prospectively provides a yield of approximately 1100 kWh/a with relatively high portion of direct irradiation in the relevant South-German region, and the average wind velocity in this area is about 6 m/s (expert system's query for this see Screen shot 1 as an example).

In due consideration of the local generation conditions thus both generation approaches, the photovoltaic and the wind energy plant, are possible in principle. But since the electric load profile largely follows the day-night cycle (Fig. 2), the expert system gives stronger support (weighting) to the photovoltaic approach, in particular for mono-crystalline cells due to the high portion of direct irradiation and the limited roof surface (higher efficiency than amorphous cells).

For the photovoltaic approach short term storage (lead acid accumulator) to cover the day-night cycle, as well as long term storage (hydrogen path) for compensation of the season based cycle, are required. Since the hydrogen storage is not desired to be installed in-house (safety reason), pressurized gas-storage located outside is proposed by the expert system (metal-hydride storage as an alternative is not favored in consequence of the temperature dependency of hydrogen output, and an additional heating system would be required).

Under consideration that a pressurized gas-storage is selected, a high pressure electrolyzer is identified to be suitable, as for charging purpose a compressor can be spared. Due to its long life-time expectancy, an alkaline electrolyzer is applicable. For electricity generation in the hydrogen path a gas-engine driven generator is decided for, due to economic and life-time reasons. In spite of the high energy densities and number of cycles, lead acid accumulators are preferred to NiMH accumulators for reasons of economy.

After the complete plant configuration was identified by the expert system, an overview of all relevant and excluded components for the considered case is displayed in a way as shown in Screen shot 2 as an example; if the preference of components chosen (e.g., renewable sources) is not distinct, this can be recognized by numbers < 999 in the result table presented by the expert system. An indication why alternative solutions were not favored can be polled by use of the explanation functionality of the tool: the expert system displays the corresponding rule(s) and weighting(s), see Screen shot 5.

In order to give a survey, in Fig. 3 the resulting configuration of the application with the selected components is displayed graphically.

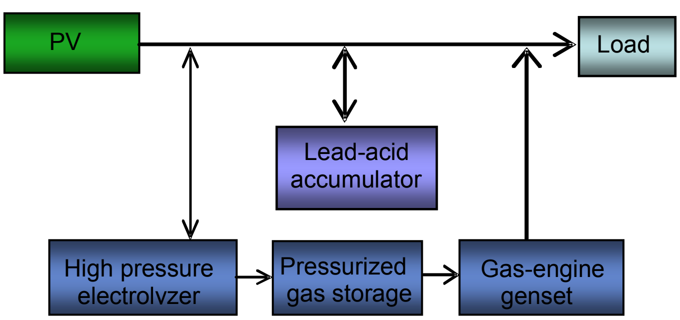


Fig. 3. Configuration of components for remote summer residences.

B. *Change of Site Conditions*

In order to demonstrate the extensive impact of a (rather small) change in the location conditions, it is now assumed that the roofs of the three summer houses have east-west alignment instead of south orientation: in this case the prospective solar energy harvest is below the threshold value, the photovoltaic approach is excluded, and wind generation is proposed by the expert system. This will also impact the size of the storages, as to bridge periods of calm wind a mid-term storage is necessary. The mid-term storage is, as in the first case, provided by means of pressurized gas; hence, the same alkaline electrolyzers and gas-engine driven generator gain application.

C. *Telecommunication Base Station*

In the next example case a remotely located telecommunication base station situated in northern Germany is regarded. Due to the location a connection to the electrical grid is not possible; therefore the supply should be realized by use of renewable energy sources in self-sufficient manner. The considered UMTS node possesses a predominant constant load of 750-1000 W (compare Table 1).

The expert system's selection starts with checking the expected renewable energy harvest at the location considered. Solar panels are excluded since the irradiation of less than 900 $kWh/(m^2 \cdot a)$ is insufficient, and in addition a great deal consists of diffuse radiation; furthermore, a sufficient area of south-oriented rooftops for solar panels is unavailable. On the other hand, the expert system's query for the average wind velocity for this region was answered with a value of 6 m/s and thus above the threshold; a wind generator installation under regard of the available area and building regulations is possible. In consequence, the expert system proposes a wind energy plant as the most likely choice. Rather, a mid-term storage system to bypass calm wind periods is required, which the expert system generally proposes as hydrogen storage.

Since the expert system's query for innovation openness was answered positively and inside installation of the hydrogen storage is admissible, a metal hydride storage is proposed. In consequence, a low-pressure PEM electrolyzer is chosen as reasonable solution for storage loading. For the electricity generation side, both predominant constant load profile as well as potential use of the fuel cell's waste heat for tempering the metal hydride storage during unloading justify the application of a PEM fuel cell which is proposed as first choice. A short term storage is not foreseen in consequence of the continuous load. The selected components result in the power supply structure as shown in Fig. 4.

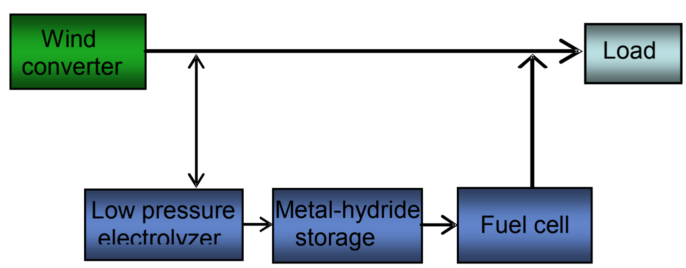
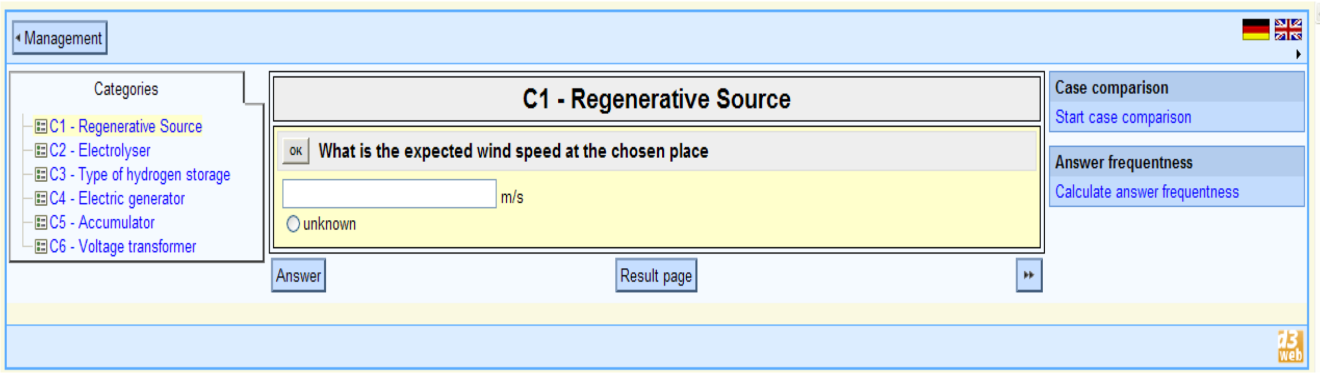


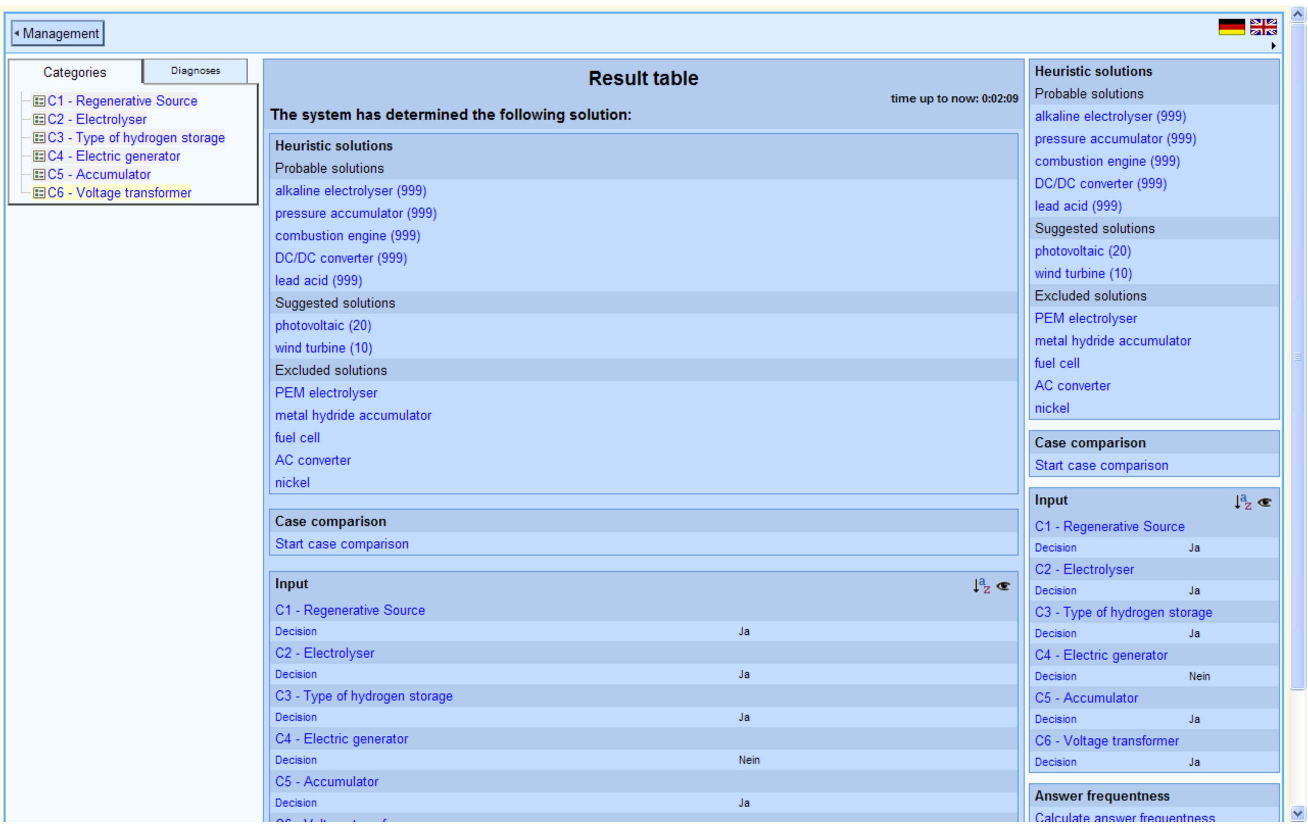
Fig. 4. Configuration of components for telecommunication base station.

VI. Conclusion and Outlook

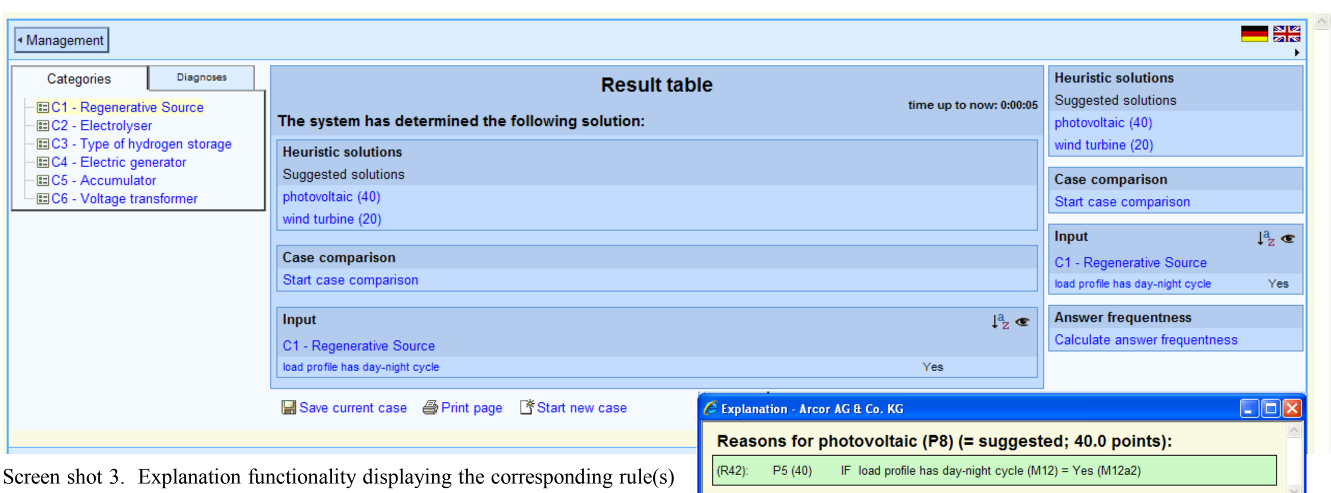
An expert system provides appropriate selection of generation and energy storage components for self-sustained and renewables based electricity supply of small applications such as telecommunication bases or remote buildings. The chosen approach features convenient set-up, easy use and transparency in reasoning which was demonstrated with some example cases. The work presented here will further be integrated as initial part-system of a three step design tool for composition, dimensioning and operational optimization of decentralized power supply systems which is presently under development, and which will completely be reported in due time, too.



Screen shot1. Expert system's query for wind speed.



Screen shot 2. Overview of all relevant and excluded components.



Screen shot 3. Explanation functionality displaying the corresponding rule(s) and weighting(s).

VII. Acknowledgment

The support for this work by the German Federation of Industrial Research Associations (AiF) is gratefully acknowledged by the authors.

VIII. 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 5Kwp 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] 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.
[7] 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.
[8] B. Pau, 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.
[9] 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.
[10] B.D. MacDonald, A.M. Rowe, “Experimental and numerical analysis of dynamic metal hydride hydrogen storage systems”, Journal of Power Sources, 174, 2007.
[11] D. Shapiro, J. Duffy, M. Kimble, M. Pien, “Solar-powered regenerative PEM electrolyser/ fuel cell system”, Solar Energy, 79(5), 2005.
[12] 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.
[13] KnowMe: http://www.d3web.de

IX. Biographies

Maike Stark, born in 1983, received the M.Sc. degree in electrical engineering from Duesseldorf University of Applied Sciences in 2008. Subsequently she joined the el. power systems institute of Duisburg-Essen-University for pursuing her PhD degree in the area of decentralized power supply.

Matthias Hausmann, born in 1983, received the B.Sc. degree in industrial engineering from the University of Duisburg-Essen in 2007. Currently he finalizes his master studies in the same subject, writing his thesis on the expert system described.

Gerhard Krost (M’1999), born in 1953, received the diploma degree in power systems engineering from Darmstadt Technical University in 1978. Working at Erlangen University from 1978 to 1985 in the field of power system harmonics calculation and measurement he received his doctoral degree in 1983. Since 1985 he is with the University of Duisburg-Essen, engaged in analysis, measurement, simulation and control of bulk and decentralized power systems. In 1998 he was appointed as a professor. Gerhard Krost is member of CIGRE, IEE, IEEE and VDE. e-mail: gerhard.krost@uni-due.de