JET Volume 6 (2013), p.p. 11 - 24

Issue 3, August 2013

http://www.fe.um.si/en/jet.html

HYDROGEN TECHNOLOGIES IN A SELF-SUFFICIENT ENERGY SYSTEM WITH RENEWABLES

VODIKOVE TEHNOLOGIJE V SAMOZADOSTNEM ENERGETSKEM SISTEMU Z OBNOVLJIVIMI VIRI ENERGIJE

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Keywords: experimental evaluation of numerical model, hydrogen technologies, reference household, renewable energy sources, self-sufficient energy system

Abstract

A potential solution for stand-alone power generation is to use hybrid energy systems with hydrogen energy storage. In this paper, a pre-feasibility study of using a 100% renewable hybrid energy system (solar and wind energy source) with hydrogen technologies (electrolyser, hydrogen tank, fuel cell) for a reference household application in Portorož, Slovenia is examined and explained. The HOMER software tool is used for simulations and optimal energy system identification, in which geographical location and availability of energy sources, load dynamics, component technical and economical characteristics are considered. The experimental work was performed on existing laboratory facilities with hydrogen technologies. The optimal feasible system capacity (34 kW), with the lowest total net present value (€138,452), is approximately eight times larger than peak power demand (3,8 kW). Experiments confirmed adequate numerical model design with an only 3% deviation in results.

Povzetek

Uporaba hibridnih energetskih sistemov s hranjenjem energije v obliki vodika predstavlja možno rešitev samozadostne preskrbe z energijo. V tem prispevku je predstavljena numerična analiza in eksperimentalna evalvacija električne preskrbe referenčnega gospodinjstva v Portorožu

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izključno na osnovi obnovljivih virov energije (sonce, veter) in z uporabo vodikovih tehnologij (elektrolizer, plinohram, gorivna celica). Za simulacijo obratovanja in določitev optimalne konfiguracije energetskega sistema je bilo uporabljeno programsko okolje HOMER, za eksperimentalno delo pa obstoječi demonstracijski laboratorij z vodikovimi tehnologijami. Optimalna rešitev je izbrana z upoštevanjem geografske lokacije in razpoložljivosti virov energije, dinamiko porabe električne energije ter tehnoloških in ekonomskih značilnosti posameznih komponent. Optimalni energetski sistem z najnižjo neto sedanjo vrednostjo projekta (138.452 €) potrebuje za pokritje električne porabe skoraj 8-krat večjo (34 kW) nazivno moč tehnologij obnovljivih virov od maksimalne konične moči (3,8 kW). Eksperimentalno obratovanje potrjuje ustreznost numeričnega modela, saj je razlika v rezultatih majhna (3 %).

1 INTRODUCTION

Meeting increasingly stringent environmental standards is often achieved by increasing the share of intermittent renewable energy sources (RES) in an energy system. Due to the misalignment of energy production and demand, the use of energy storage is usually required, [1]. The use of renewables, coupled with hydrogen (storage) technology, is a viable solution, [2–4]. Furthermore, hydrogen technologies can also be used in a variety of hybrid energy systems, including biomass-based energy systems, [5], and integrated gasification combined cycle plants with CO2 capture, [6].

The following technical and economic analyses of RES energy systems with hydrogen storage have already been discussed: modelling stand-alone applications [2], [7–13], modelling integrated or grid connected applications [14–17] and operational experience, [18].

An RES-hydrogen energy system for a self-sufficient household is described in this study, as schematically shown in Fig. 1. In this example, hydrogen is produced by an electrolyser (and stored in a tank) powered by the surplus electricity from renewable energy technologies, using solar and wind (specifically at summer daytime). When RES are scarce, or demand is high, additional power is needed, so the fuel cell re-powers, using hydrogen gas, to produce electricity (usually at night and winter).

2 METHODS

The scope of this work is, first, to model a feasible configuration of a self-sufficient energy system based on RES and hydrogen technologies for a remote household located in Slovenia and, second, to experimentally validate the results of system operation. In this study, only electricity is considered. Experimentally, only hydrogen technologies are validated, while renewables are only simulated.

The HOMER[1] numerical simulation tool was used to determine optimal energy system configuration, [19]. The analysis is based on the actual geographical location, availability of energy sources, load dynamics and technical and economical characteristics of system components. An existing system with hydrogen technologies, established within Centre of

[1] http://homerenergy.com/pdf/homergettingstarted268.pdf

Excellence for Low Carbon Technologies (CO NOT), was used for experimental evaluation of the numerical results.

2.1 Energy system model and simulation

The RES-hydrogen energy system operation was determined via numerical simulation with the aid of the HOMER software tool. HOMER models an energy system's physical behaviour and its life-cycle cost, which is the total cost of installing and operating the system over its life span. It is an input/output model, making annual analyses in steps of one hour. General inputs are demands, capacities, component technical characteristics and costs. Outputs are energy balances, capacities, resulting annual production and life-cycle costs.

In this paper, the energy supply of a stand-alone household, located in Slovenia, is considered. In the model (Fig. 1), AC electrical load is supplied, via DC-AC inverter, primarily by wind turbines and photovoltaic panels. Excess electricity produced from RES is stored as electrolytically produced hydrogen. When primary RES are scarce or unavailable, the fuel cell system produces power from stored hydrogen.

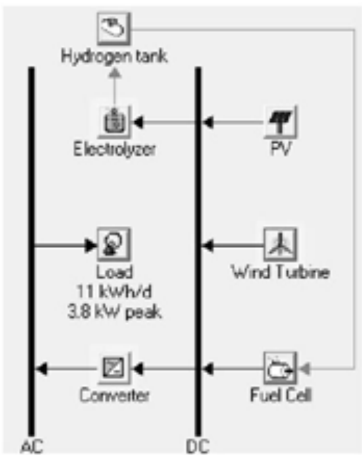

Figure 1: *HOMER numerical model of a stand-alone energy system*

2.1.1 Hourly input distributions

Actual input data time series, needed for the analysis, were obtained from real measurements. Electricity consumption data (Fig. 2) were taken from MeRegio and Mirabel projects, [20]. From among 87 consumers, a case with 11 kWh of daily power consumption was chosen. Wind and solar energy resources in Portorož, Slovenia are considered in this study. Meteorological data were acquired from ARSO's (Slovenian Environment Agency) test reference year, with annual average wind speed of 2.8 m/s, peaking at 10.6 m/s and annual average daily global horizontal radiation 3.9 kWh/m², [21]. The test reference year is historical digital data set that represents measured 365-day values of the selected meteorological variables on an hourly basis. The sequence is synthetically constructed using monthly values selected from a multiple year data set for a given location, so that the resulting test reference year is typical for the location.

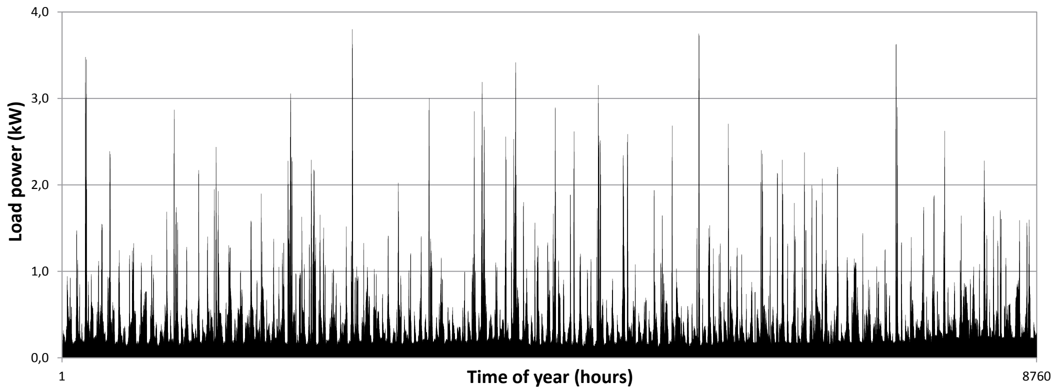

Figure 2: *Hourly electricity consumption for a one-year period*

2.1.2 Energy system components

Conversion of solar radiation to electrical energy is achieved with a photovoltaic array (PV). The power output of the PV array depends on the amount of radiation striking its surface, which is generally not horizontal. Therefore, in each time step, HOMER calculates the global solar radiation on the surface of the PV array. In the calculation of PV power output, its rated capacity, derating factor, solar radiation, temperature coefficient of power and PV cell temperature are considered, [22].

A wind turbine converts wind kinetic energy to electrical energy. Its power depends on wind speed, adjusted to hub height, and wind turbine power curve. The cut-in wind speed of the chosen wind turbine equals 3 m/s and at wind speeds 13 m/s it reaches peak output power.

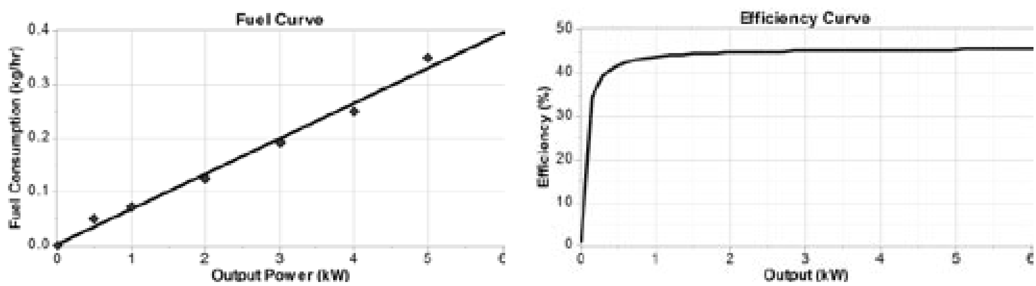

Figure 3: *Fuel cell fuel curve and efficiency, experimentally determined within CO NOT*

The hydrogen production rate is defined by electrolyser efficiency and minimum load ratio (technical minimum). Experimentally determined values, acquired within the Centre of Excellence for Low-Carbon Technologies (CO NOT), 72 and 50% respectively, were used. Hydrogen consumption is calculated using fuel curve and fuel cell electric efficiency is determined based on higher heating value, 142 MJ/kg. The hydrogen tank is a container used to store produced hydrogen for later use. The fuel cell system is used to re-power stored

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hydrogen, when there is not enough RES. The fuel cell power production depends on the fuel curve. An experimentally defined fuel curve and its corresponding efficiency are shown in Fig. 3.

2.1.3 Boundary conditions and optimisation

HOMER simulates different system configurations with several combinations of components (and their sizes) that are specified in the components inputs. All feasible system configurations are then listed in order from most cost-effective to least cost-effective, based on its net present value (NPV).

The project's lifetime is assumed to be 20 years, as well as all components' lifetime, except for the fuel cell, which has to be replaced every 20,000 operating hours. The annual real interest rate considered in the model was 6 %.

Table 1 shows component parameters as boundary conditions of the model. PV array and wind turbine sizes considered in the calculation were 10 to 30 and 5 to 20 kW, respectively. Electrolyser, fuel cell and converter sizes between 1 and 6 kW were considered. Capital costs of investment are based on invoices acquired within the project in CO NOT. Operation and maintenance (O&M) costs are based on [12].

Table 1: *Considered input component parameters*

Component	Size (kW)	Capital cost (€/kW)	O&M (% of capital cost)
PV array	10–30	1.500	0
Wind turbine	5–20	1.100	1
Electrolyser	3–6	8.000	2
Fuel cell	1–5	4.000	2,5
Power converter	4	800	0
Component	**Size (kg)**	**Capital cost (€/kg)**	**O&M (% of capital cost)**
Hydrogen tank	0–60	500	0,5

2.2 Experimental system with hydrogen technologies

An experimental system, installed at the Šoštanj thermal power plant in Šoštanj, Slovenia, was used to provide operational evaluation of hydrogen technologies in the above-described manner and calculated beforehand with simulations performed by the HOMER numerical model. The schematic of the system is shown in Fig. 4 and its photograph in Fig. 5. It is composed of alkaline electrolyser (Hydrogenics HySTAT) with 120 kW_e nominal capacity, hydrogen production rate up to 15 Nm^3/hr at 25 bar. The hydrogen tank size is 20 m^3. The PEM-type fuel cell UPS system (Future-E Jupiter) delivers 6 kW_e of power. Additional equipment consists of an electronic load (Amrel PLW) with cooling unit (Hidros LSK), measuring instrumentation (hydrogen mass flow meters, electric meters, pressure gauges, etc.), PLC (Mitsubishi Q series) and computer control system with remote access.

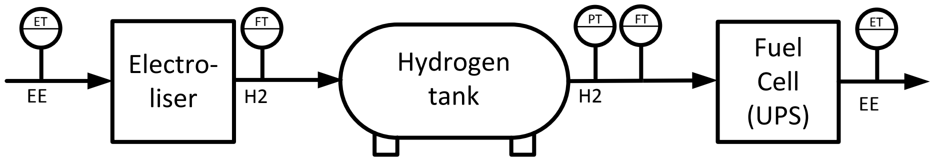

Figure 4: *General scheme of experimental system with hydrogen technologies*

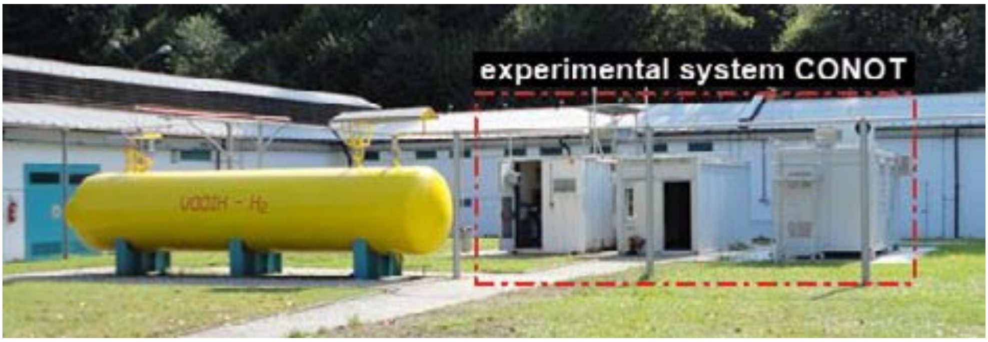

Figure 5: *Photograph of the outside of the hydrogen technology testing facilities*

3 RESULTS

3.1 Numerical simulation results

A feasible system is defined as a hybrid system configuration that is capable of meeting the load. Under given conditions, one system configuration was found feasible. It has a total of 249 different combinations of size or number of components. The optimal combination, with the lowest total net present value (€138,452), is presented in Table 2. The (levelised) cost of energy for optimal system combination is €2,901/kWh. The current electricity grid purchase price in Slovenia for households is approximately 0.15 €/kWh. Nominal primary (RES) and secondary (fuel cell) power source capacity, combined, is 34 kW, while peak demand is 3.8 kW. The optimal electrolyser and converter size is 4 kW, each, with tank capacity being 30 kg of hydrogen.

Fig. 6–Fig. 9 show major components' operating characteristics: hydrogen storage level, electrolyser power, fuel cell power and their duration curves, respectively. Hydrogen energy storage shows the ability to store inter-seasonal fluctuations in RES availability. Summers' higher RES energy density is stored to be used during colder half of the year (Fig. 6). Unlike the fuel cell (Fig. 8), the electrolyser (Fig. 7) operates during 75% of the operation time with its nominal power (Fig. 9Figure 7). In Fig. 9, the difference between electrolyser electricity consumption and fuel cell electricity production, which represents the overall efficiency of hydrogen energy storage (averaging 26%) is also shown.

Table 2: *Optimal system configuration*

Component	Size (kW)
PV array	20
Wind turbine	10
Electrolyser	4
Fuel cell	4
Power converter	4
Component	**Size (kg)**
Hydrogen tank	30

Table 3 presents an optimal system's electrical production configuration and consumption values. The PV arrays produce 80%, while the secondary power source (fuel cell) produces 9% of the electricity. The electrolyser electricity consumption rate is 69%, while the household consumes 31%. All electric load was met throughout the year, and the excess electricity is 47.5% of overall production.

Table 3: *Optimal system configuration electrical production and consumption*

Production	kWh/year	%
PV array	21,205	80
Wind turbines	3,007	11
Fuel cell	2,416	9
Total	26,629	100
Consumption	**kWh/year**	**%**
AC primary load (household)	4,161	31
Electrolyser	9,351	69
Total	13,512	100
Other	**kWh/year**	**%**
Excess electricity	12,655	47.5[a]
DC/AC conversion loss	462	11.1[b]
Unmet electric load	0	0
Capacity shortage	0	0
Renewable fraction	/	100

[a] *share of total production*

[b] *share of AC primary load*

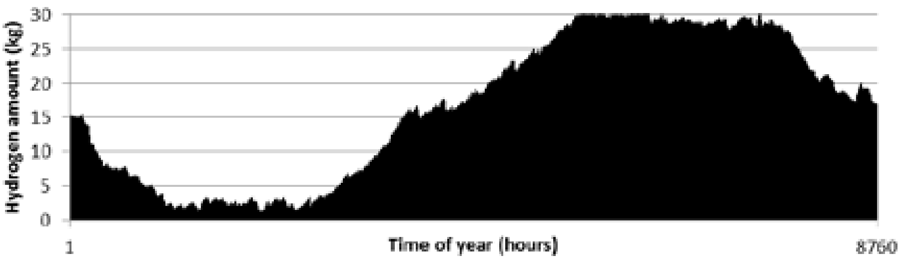

Figure 6: *Hydrogen tank storage level during the year*

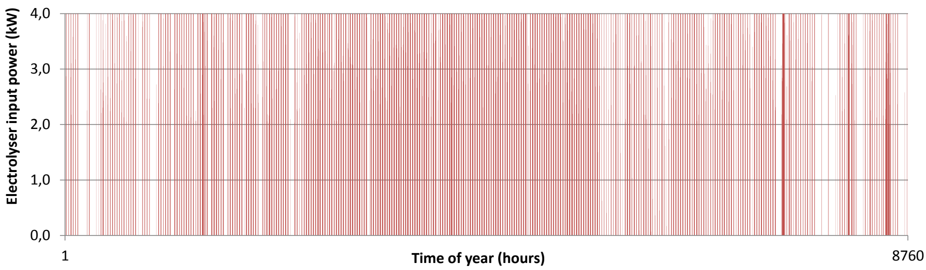

Figure 7: *Electrolyser input power: full year scale*

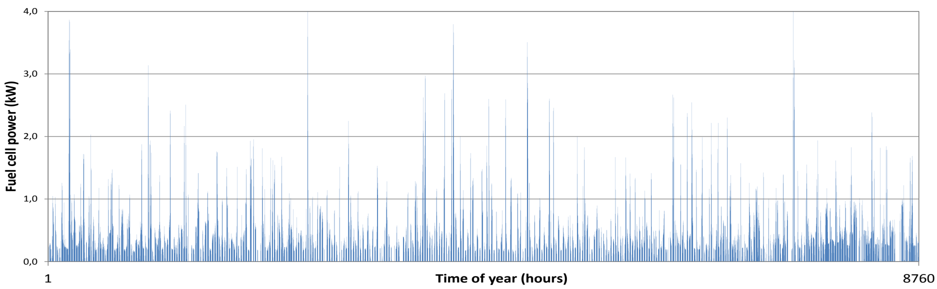

Figure 8: *Fuel cell output power: full year scale*

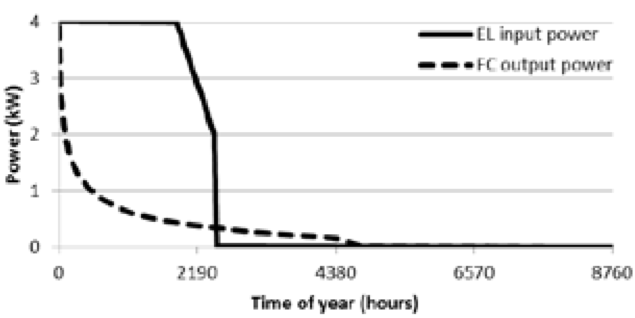

Figure 9: *Electrolyser and fuel cell duration curves*

Table 4 lists optimal system configuration characteristics, where low mean outputs and capacity factors represent its nature. Capacity factors vary from 3.4% to 12.1%, except for the electrolyser being 26.7%. Average power, from primary and secondary power sources, exceeds the average household load by 688%, the largest contribution being from photovoltaic arrays (PV) with 510% penetration. The results show similar operation time of PV and wind turbine (WT), 3,873 and 3,556 hours per year, respectively. In contrast, the electrolyser (EL) operates less frequently (2,500 hours/year) than the fuel cell (4,834 hours/year), which is also demonstrated by fewer startups. The fuel cell (FC) life span of 20,000 operating hours means that replacement is necessary after every 4.14 years. The average fuel cell electric efficiency is 42.9%.

Table 4: *Optimal system configuration characteristics*

Quantity / Component	Unit	PV	WT	FC	EL	DC/AC
Rated capacity	kW	20	10	4	4	4
Mean output	kW (kg_{H2}*)	2.4	0.34	0.5	0.07*	0.47
Minimum output	kW (kg_{H2}*)	0	0	0	0.00*	0.13
Maximum output	kW (kg_{H2}*)	17.1	9.31	4	0.07*	3.8
Capacity factor[a]	%	12.1	3.43	6.89	26.7	11.9
Component penetration[b]	%	510	72,3	105,5	/	/
Hours of operation	h/year	3,873	3,556	4,834	2,500	8,760
Full load hours	h/year	1,244	323	604	2,338	1,095
Levelised cost	€/kWh (€/kg_{H2}*)	0.123	0.355	0.79	11.50*	0.038
Number of starts	starts/year	/	/	523	395	/
Operational life	years	20	20	4.14	20	20
Fixed generation cost	€/year	/	/	0,48	/	/
Hydrogen cons./prod.	kg/year	/	/	169	171	/
Specific hydrogen cons./prod.	kg/kWh	/	/	0.07	0.018	/
Hydrogen energy input/output	kWh/year	/	/	5,627	5,694	/
Mean electric efficiency	%	/	/	42.9	72.1	90

[a] *average power output divided by the total capacity*
[b] *average power output divided by the average primary load*

3.2 Experimental results

The fact that the given experimental system configuration is unalterable prevents recreating an exact experimental match to different numerical model designs. In order to conduct an experiment in which the model and real system capacity do not match, scaling has to be applied. For the purpose of this experiment, capacity (input power), hydrogen production rate and time scaling were applied. The fuel cell system's modular design (3 × 2 kW) enabled the direct transfer of HOMER model results to be replicated in the experiment. In contrast, the electrolyser prevents any capacity adjustment; therefore, linear scaling was performed. After consulting electrolyser system operators, maximum input power in the experiment was set to 72 kW_e.

The electrolyser's experimental operation program was acquired using numerical simulation results, multiplied by 72/4. Analogue-to-input power, the hydrogen production measurements during the experiment were multiplied by 4/72. On the basis of previous experimental work conducted within CO NOT, the fast electrolyser system operation response to power changes and relatively fast start-up times (less than 10 seconds) were observed. For that reason, and due to relatively long simulation period (hourly steps in one year),the experiment's duration was limited to a period of one week in summer and scaled so that one hour in the model corresponds to one minute in the experiment. Furthermore, due to frequent start-up limitations, the electrolyser was not shut down during the experiment, but its power was reduced, as seen in Fig. 10. For the analysis, data (power and hydrogen production rate) from that period were neglected (used as zero), which is also shown in Fig. 10.

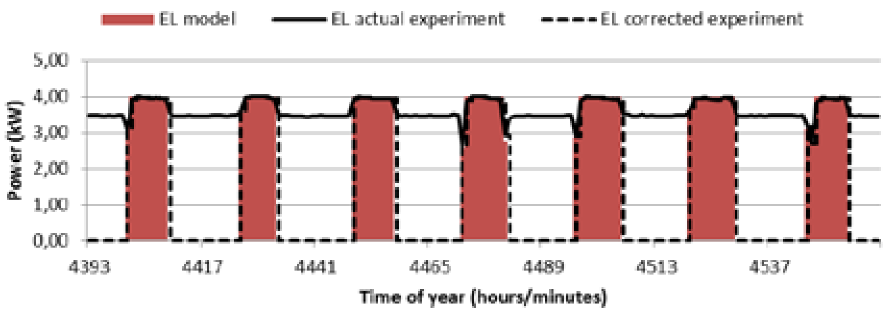

Figure 10: *Correction of experimental results by neglecting values in periods of simulated turn-off*

Fig. 11 and Fig. 12 present the chosen one-week period with both numerical and experimental results, and power and hydrogen flow rate, respectively. Fig. 12 also shows notable differences in hydrogen flow rates, which is a consequence of inaccurate or over-simplified models of both electrolysers and fuel cells in HOMER. The actual fuel cell UPS system also contains a battery, and the electrolyser contains an internal pressure buffer and hydrogen filtering discharge etc.

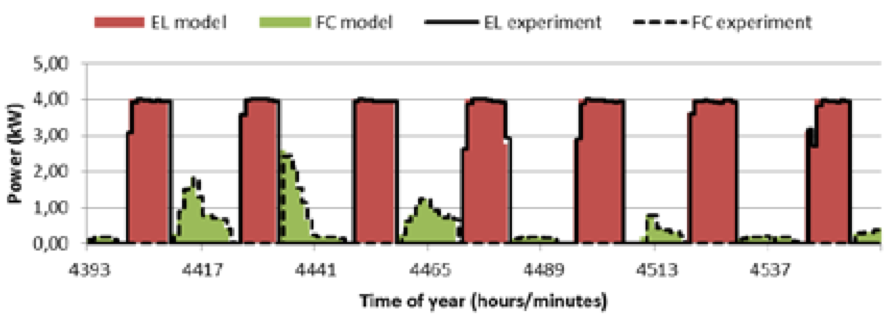

Figure 11: *Simulation and experimental power distribution of 1-week period in summer*

A comparison of integral parameters, both simulation and experiment, presented in Table 5, shows remarkably good matches of both results, with differences of less than 3%.

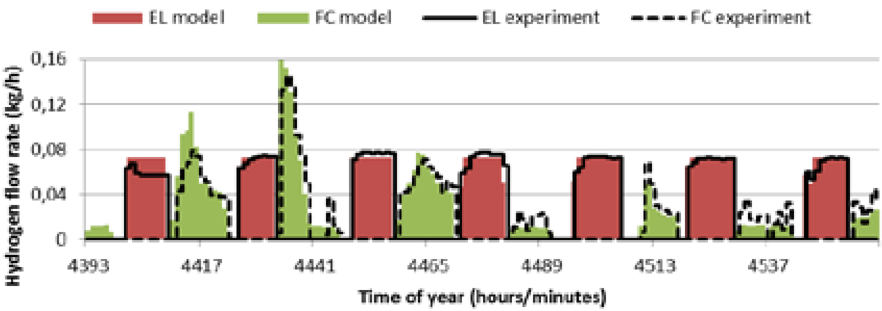

Figure 12: *Simulation and experimental hydrogen flow rate distribution of 1-week period in summer*

Table 5: *Simulation and experiment results comparison*

Parameter	Unit	EL model	EL experiment	Index	FC model	FC experiment	Index
energy	kWh	4.204	4.172	0.99	0.742	0.721	0.97
H2 amount	kg	0.077	0.075	0.97	0.046	0.045	0.98
el. efficiency	%	72.2%	70.9%	0.98	40.9%	40.6%	0.99

4 DISCUSSION

In this paper, a numerical model of an RES-hydrogen energy system was experimentally validated with a mere 3% difference in results. The proposed method was proven suitable for the system planning and design of hybrid energy. Therefore, sustainable and renewable energy supply of a stand-alone household in Portorož is technologically feasible with the use of 100% RES in a combination with hydrogen technologies, although costly due to large and expensive RES capacities. The turnover point is at an electricity grid purchase price increase of over 200% (from €0.15 to 0.45 /kWh) and the simultaneous decrease of RES technology costs by up to 80% and an increase in its efficiency.

The discussed energy system requires large production capacity, which results in considerable excess electricity production (almost 50%) and low energy utilisation (low capacity factor). Due to low resource availability and intermittent seasonal energy, large capacity storage is required. However, the ability to store hydrogen between seasons is uncommon in comparison to most other storage technologies and in this regard presents its advantage. The weakness of hydrogen storage is best indicated by its low overall energy efficiency of 26%. Potential technical development could, however, increase storage efficiency to approximately 50%.

Currently available and the most common hydrogen technology (PEM fuel cell UPS and alkaline electrolyser) has been shown to be fairly suitable for considered dynamic power balancing

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operation with fluctuating renewables. The UPS system successfully meets the simulation requirements for fast start ups and power ramping, while electrolyser simulation shows that it mostly operates at constant load; therefore, only its fast startups are required. Considering minor changes in current alkaline electrolyser system design (e.g. uniform cooling system installation in series with fuel cell for cool down prevention and shutdown hydrogen depressurisation disabling) hydrogen production could be started quickly, within minutes. Hydrogen technology's dynamic operation for balancing power supply and demand requires frequent startups and shutdowns (approximately 1.5 times per day) which negatively affects the equipment's lifespan. It must also be noted that single household consumption is the most extreme case in terms of power fluctuation and supplying aggregated consumers (several household or community) would decrease the relative system operation dynamics.

Scaling results, of a fuel cell or electrolyser, linearly, raises a question of accuracy. Some error in results and reduced relevance could rightly be recognized. Arguments in favour of this method (linear scaling) are the fact that (a) fuel cells (and electrolysers, since it is essentially the same process) are unique as energy converters, i.e. their range of application (in terms of power and use) far exceeds all other types [23], (b) most auxiliary power is used for cooling which is proportional to power, (c) one large unit in the model can in reality be substituted by several smaller ones (dispersed or centralised), and (d) EL and FC are both in essence already composed of multiple individual cells (forming stack), implying their fundamental ability to scale.

Acknowledgements

This research is partly financed by the European Union, European Social Fund.

Part of the presented work has been accomplished within the Centre of Excellence for Low-Carbon Technologies (CO NOT), Hajdrihova 19, 1000 Ljubljana, Slovenia.

This work was supported also by INEA d.o.o., Stegne 11, 1117 Ljubljana, Slovenia and Termoelektrarna Šoštanj d.o.o., Cesta Lole Ribarja 18, 3325 Šoštanj.

References

[1] **B. V. Mathiesen and H. Lund,** *Comparative analyses of seven technologies to facilitate the integration of fluctuating renewable energy sources*, IET Renewable Power Generation, vol. 3, no. August 2008, pp. 190–204, 2009.

[2] **K. Agbossou, R. Chahine, J. Hamelin, F. Laurencelle, A. Anouar, J.-M. St-Arnaud, and T. K. Bose,** *Renewable energy systems based on hydrogen for remote applications*, Journal of Power Sources, vol. 96, no. 1, pp. 168–172, Jun. 2001.

[3] **F. Barbir,** *PEM electrolysis for production of hydrogen from renewable energy sources*, Solar Energy, vol. 78, no. 5, pp. 661–669, May 2005.

[4] **B. V. Mathiesen and H. Lund,** *Fuel-efficiency of hydrogen and heat storage technologies for integration of fluctuating renewable energy sources*, in 2005 IEEE St. Petersburg powertech : conference proceedings, 2005, pp. 1–7.

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[5] **A. Pirc, M. Sekavčnik, and M. Mori,** *Universal Model of a Biomass Gasifier for Different Syngas Compositions*, Strojniški vestnik – Journal of Mechanical Engineering, vol. 58, no. 5, pp. 291–299, May 2012.

[6] **A. Lotrič, M. Sekavčnik, C. Kunze, and H. Spliethoff,** *Simulation of Water-Gas Shift Membrane Reactor for Integrated Gasification Combined Cycle Plant with CO2 Capture*, Strojniški vestnik – Journal of Mechanical Engineering, vol. 57, no. 12, pp. 911–926, Dec. 2011.

[7] **A. Pirc, M. Sekavčnik, B. Drobnič, and M. Mori,** *Use of hydrogen technologies for saving electric energy in combination with renewable energy systems*, in 6th International Workshop on Deregulated Electricity Market Issues in South-Eastern Europe, 2011.

[8] **R. Dufo-López and J. L. Bernal-Agustín,** *Multi-objective design of PV–wind–diesel–hydrogen–battery systems*, Renewable Energy, vol. 33, no. 12, pp. 2559–2572, Dec. 2008.

[9] **S. Kelouwani, K. Agbossou, and R. Chahine,** *Model for energy conversion in renewable energy system with hydrogen storage*, Journal of Power Sources, vol. 140, no. 2, pp. 392–399, Feb. 2005.

[10] **M. J. Khan and M. T. Iqbal,** *Pre-feasibility study of stand-alone hybrid energy systems for applications in Newfoundland*, Renewable Energy, vol. 30, no. 6, pp. 835–854, May 2005.

[11] **B. Shabani, J. Andrews, and S. Watkins,** *Energy and cost analysis of a solar-hydrogen combined heat and power system for remote power supply using a computer simulation*, Solar Energy, vol. 84, no. 1, pp. 144–155, Jan. 2010.

[12] **E. I. Zoulias and N. Lymberopoulos,** *Techno-economic analysis of the integration of hydrogen energy technologies in renewable energy-based stand-alone power systems*, Renewable Energy, vol. 32, no. 4, pp. 680–696, Apr. 2007.

[13] **S. R. Vosen and J. O. Keller,** *Hybrid energy storage systems for stand-alone electric power systems: optimization of system performance and cost through control strategies*, International Journal of Hydrogen Energy, vol. 24, pp. 1139–1156, 1999.

[14] **D. Anderson and M. Leach,** *Harvesting and redistributing renewable energy: on the role of gas and electricity grids to overcome intermittency through the generation and storage of hydrogen*, Energy Policy, vol. 32, no. 14, pp. 1603–1614, Sep. 2004.

[15] **J. Barton and R. Gammon,** *The production of hydrogen fuel from renewable sources and its role in grid operations*, Journal of Power Sources, vol. 195, no. 24, pp. 8222–8235, Dec. 2010.

[16] **M. Beccali, S. Brunone, M. Cellura, and V. Franzitta,** *Energy, economic and environmental analysis on RET-hydrogen systems in residential buildings*, Renewable Energy, vol. 33, no. 3, pp. 366–382, Mar. 2008.

[17] **J. L. Bernal-Agustín and R. Dufo-López,** *Techno-economical optimization of the production of hydrogen from PV-Wind systems connected to the electrical grid*, Renewable Energy, vol. 35, no. 4, pp. 747–758, Apr. 2010.

[18] **a. M. Chaparro, J. Soler, M. J. Escudero, E. M. L. de Ceballos, U. Wittstadt, and L. Daza,** *Data results and operational experience with a solar hydrogen system*, Journal of Power Sources, vol. 144, no. 1, pp. 165–169, Jun. 2005.

[19] **R. Lacko, B. Drobnič, M. Mori, and M. Sekavčnik,** *Planning of a self-sufficient energy system with 100% renewable energy sources and hydrogen storage*, in Power Engineering, 22nd International Expert Meeting, 2013.

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[20] **G. Černe, Z. Marinšek, and others,** *MIRABEL, Micro-request-based aggregation, forcasting and scheduling of energy demand, supply and distribution*, Ljubljana, 2011.

[21] **Slovenian Environment Agency,** *Test reference year*, Ljubljana, 2008.

[22] **T. Lambert, P. Gilman, and P. Lilienthal,** *Micropower system modeling with Homer*, in Integration of Alternative sources of Energy, John Wiley & Sons, 2006, pp. 379–418.

[23] **J. Larminie and A. Dicks,** Fuel Cell Systems Explained. Chichester: John Wiley & Sons, 2003, p. 433.