PLANNING OF A SELF-SUFFICIENT ENERGY SYSTEM WITH 100% RENEWABLE ENERGY SOURCES AND HYDROGEN STORAGE

Rok LACKO, Boštjan DROBNIČ, Mitja MORI, Mihael SEKAVČNIK

POVZETEK

Uporaba hibridnih energetskih sistemov s hranjenjem energije v obliki vodika, predstavlja možno rešitev samozadostne preskrbe z energijo. V tem prispevku je predstavljena analiza električne preskrbe referenčnega gospodinjstva v Portorožu, izključno na osnovi obnovljivih virov energije (sonce, veter) in uporabo vodikovih tehnologij (elektrolizer, plinohram, gorivna celica). Za simulacijo obratovanja in določitev optimalne konfiguracije energetskega sistema je bil uporabljen numerični program HOMER. Optimalna rešitev je izbrana z upoštevanjem geografske lokacije in razpoložljivosti virov energije, dinamiko električne porabe ter tehnoloških in ekonomskih značilnosti posameznih komponent. Oddaljeno gospodinjstvo s povprečno dnevno električno porabo 11 kWh, konične moči 3,8 kW je obravnavano kot samozadostno. Rezultati prikazujejo energetski sistem z najnižjo neto sedanjo vrednostjo projekta. Izkaže se, da je potrebna nazivna moč tehnologij obnovljivih virov skoraj 10-krat večja (34 kW) od maksimalne porabe.

Ključne besede: samozadostni energetski sistem, obnovljivi viri energije, vodikove tehnologije, hibridni energetski sistemi

ABSTRACT

A potential solution for stand-alone power generation is to use a hybrid energy systems with hydrogen energy storage. In this paper, a pre-feasibility study of using 100% renewable hybrid energy system (using solar and wind energy source) with hydrogen technologies (electroyser, hydrogen tank, fuel cell) for a reference household application in Portorož, Slovenia is explained. HOMER software tool is used for simulations and optimal energy system determination, where geographical location and availability of energy sources, load dynamics, component technical and economical characteristics were considered. A remote household with electricity consumption of 11 kWh/day with a 3,8 kW peak power demand was considered as the stand alone load. Results show the optimal feasible system with lowest total net present cost. It was found that almost a ten-fold (34 kW) renewable technology capacity is required to meet the demand.

Keywords: self-sufficient energy system, renewable energy sources, hydrogen technologies, hybrid energy systems

1. INTRODUCTION

Diminishing fossil fuel reserves have led to the increased awareness of energy resource use. The last decade has seen rapid development and deployment of renewable energy technologies [1]. Their decentralised character and low polluting operation makes their use attractive also to private consumers, such as households. Such systems are especially relevant to off-network consumers, remote areas or sensitive natural environments [2–4].

A renewable energy only based system is subjected to the intermittent nature of renewable energy sources (RES), like wind and solar, which exhibit strong short-term and seasonal variations in their energy outputs. Therefore, there is a need to store surplus energy produced in period of low demand in order to stabilise the output when the demand is high. Several studies discuss the use of hydrogen as an energy carrier in a RES based stand-alone energy system [5–7].

Hydrogen is produced by an electrolyser powered by the surplus electricity from renewable energy technologies. This is especially the case at high RES density, at midday or in summer. Produced hydrogen is then stored in a pressurised tank for later use. When additional power is needed, the fuel cell re-powers hydrogen gas to produce electricity. Fuel cell often operates as a secondary power source at night or when renewable sources are scarce.

The objective of this study is finding a feasible configuration of a self-sufficient energy system based on RES and hydrogen technologies for a remote household application located in Slovenia. HOMER simulation tool was used to determine optimal energy system configuration. Analysis is based on real geographical location and availability of energy sources, load dynamics, components technical and economical characteristics.

2. HYBRID ENERGY SYSTEM

A hybrid energy system consists of several different energy technologies, often a combination of renewable and non-renewable energy sources, working in parallel, including energy storage units. Fig. 1 a) outlines a general scheme of a stand-alone power generation system.

Fig. 1 b) shows the proposed system configuration as implemented in the HOMER simulation tool. 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 not available, the fuel cell system produces power from stored hydrogen.

The general scheme outlined in Fig. 1 is reflected in the HOMER model. Additional information for load, resources, etc. are described in the following sections.

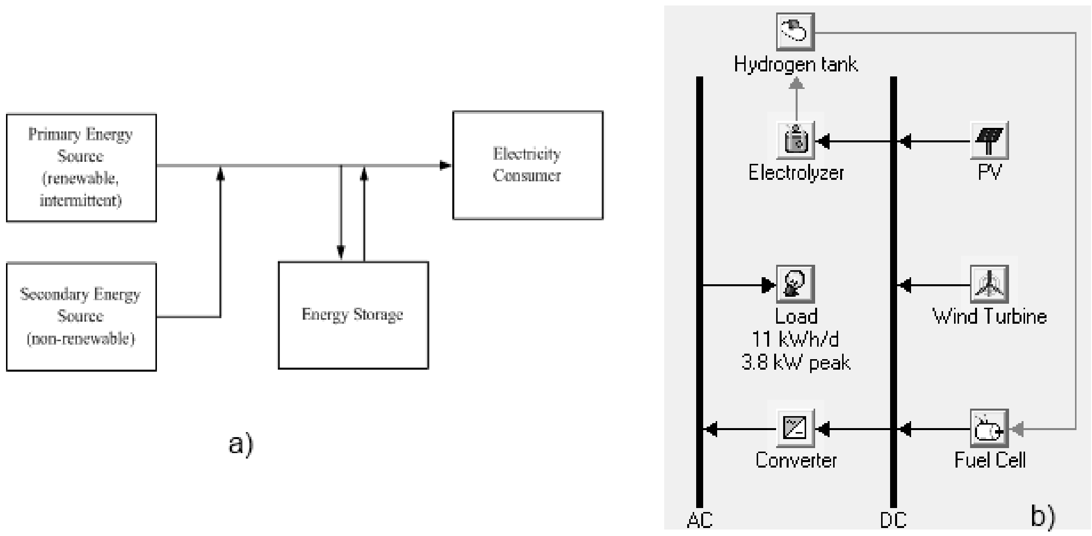

Fig. 1: General scheme (a) and HOMER set-up (b) of a stand-alone power generation system.

2.1 Electricity consumer

The analysis is based on the temporal set of the single household consumption from MeRegio and Mirabel projects [8]. Measurements were taken from November 2009 till August 2010. Yearly consumption data set was synthetically constructed by filling the missing autumn data with existing spring consumption values. Between 87 consumers the one with 11 kWh of daily consumption has been chosen as this value matches results from other sources [9]. Hourly data were obtained in the scheme with a single tariff.

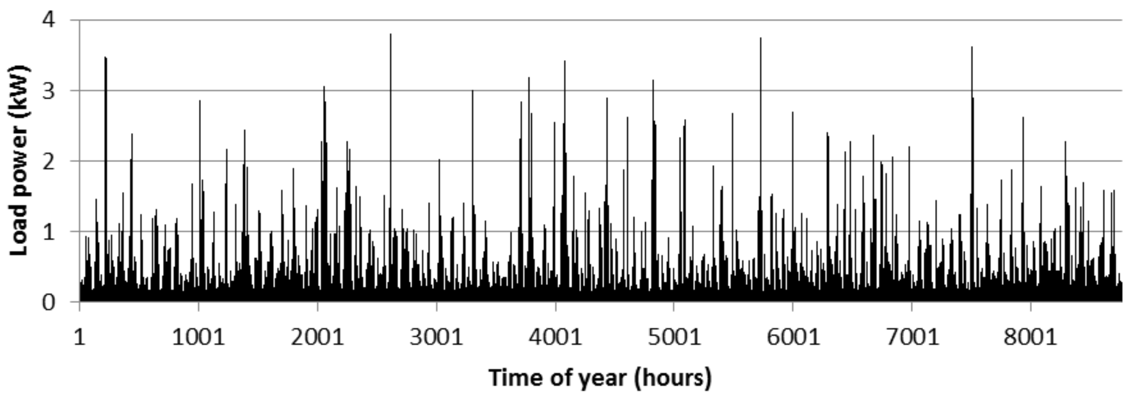

Fig. 2: Hourly electricity consumption for a one year period

2.2 Renewable resources

Wind and solar energy resources of Portorož, Slovenia are considered in this study. Meteorological data were acquired from ARSO's (Slovenian Environment Agency) test reference year [10]. Test reference year is historical digital data set that represents 365-day series of real measured hourly values of the selected meteorological variables. The sequence is synthetically constructed using monthly values selected from a multiple year data set of observations for a given location such that the resulting test reference year is typical for the location.

Reference wind speed monthly average for Portorož Airport is shown on Fig. 4. Annual average speed is 2,8 m/s, peaking 10,6 m/s.

Fig. 5 shows daily global horizontal radiation in Portorož, with the annual average daily radiation 3,9 kWh/m^2.

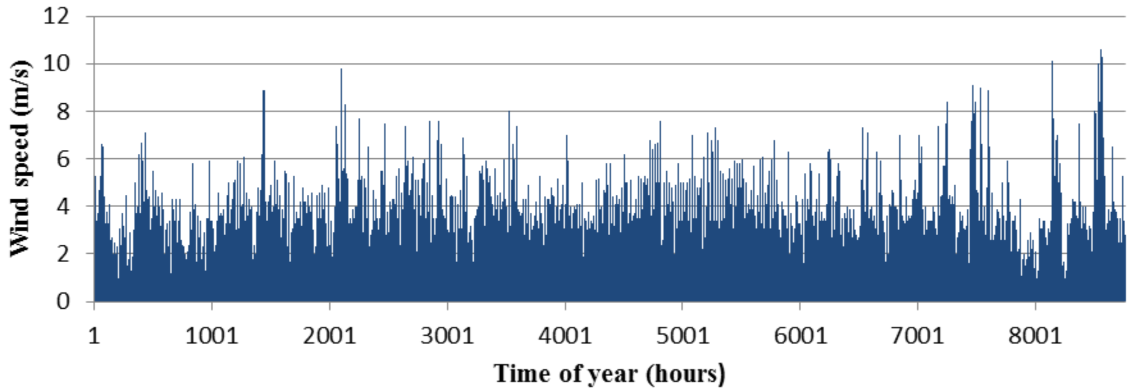

Fig. 3: Test reference wind speed monthly averages

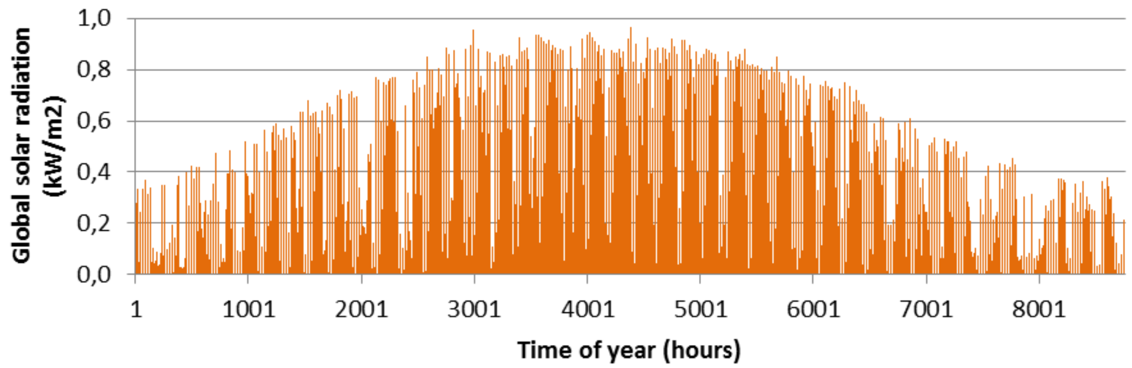

Fig. 4: Test reference solar radiation on ground

2.3 Hybrid system components

1) Conversion of solar radiation to electrical energy is achieved with photovoltaic array (PV) utilizing photovoltaic effect. Power output of the PV array depends on the amount of radiation striking the surface of the PV array, which in general is not horizontal. So in each time step, HOMER must calculate the global solar radiation incident on the surface of the PV array. In calculating PV power output its rated capacity, derating factor, radiation incident on the PV array, temperature coefficient of power and PV cell temperature are considered [11].

2) Wind turbine converts wind kinetic energy to electrical energy. Its power depends on wind speed (Fig. 4), adjusted to hub height, and wind turbine's power curve (Fig. 6) [11]. Cut-in wind speed of the chosen wind turbine equals 3 m/s, at wind speeds 13 m/s it reaches peak output power.

3) Additional energy that is available, but not used by the load (reference household), is used to operate electrolyser to produce hydrogen gas. Hydrogen is an energy carrier that is used to efficiently store the energy. Excess electricity occurs when there is a surplus of power being produced (either by a renewable source or by the generator when its minimum output exceeds the load) but the electrolyser or storage is unable to absorb it all. 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 mass flow rate is calculated based on higher heating value, 142 MJ/kg.

4) Hydrogen tank is a container used to store produced hydrogen for later use. Hydrogen is used in fuel cell when needed.

5) Fuel cell system is used to re-power stored hydrogen, when there is not enough renewable sources. Fuel cell power production depends on fuel curve. Experimentally defined fuel curve and corresponding efficiency are shown on Fig. 7.

6) A power electronic converter is needed to maintain the flow of energy between the ac and dc components. Efficiency considered in this analysis is 90 %.

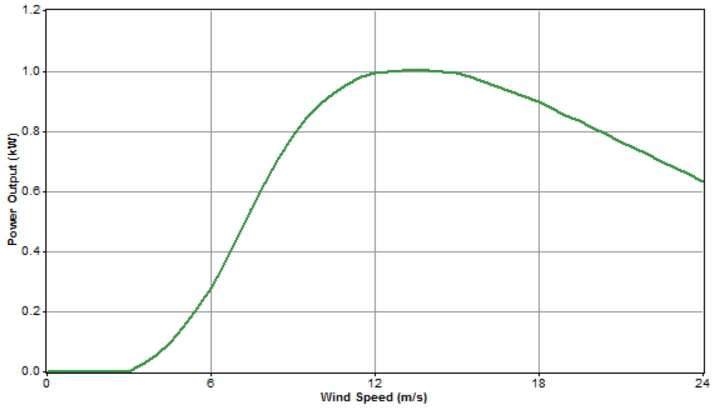

Fig. 5: Wind turbine power curve used in HOMER

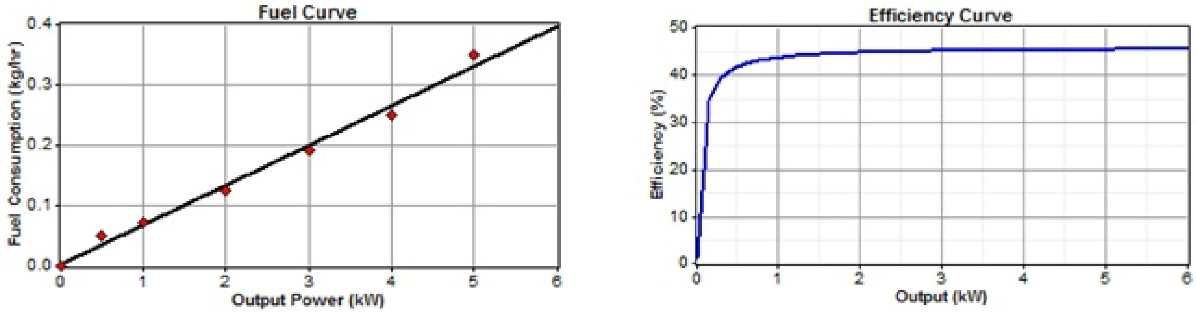

Fig. 6: Fuel cell fuel curve and efficiency

3. OPTIMISATION

For this analysis HOMER, a sizing and optimisation tool is used. It simulates system configurations with all of the combinations of components (and their sizes) that are specified in the components inputs. HOMER discards from the results all infeasible system configurations, which are those that do not adequately meet the load given, either available resource or constraints that are specified [11]. All feasible system configurations are then listed in order of most cost-effective to least cost-effective. The cost-effectiveness of a system configuration is based on its net present cost.

Project lifetime is assumed to be 20 years, as well as all components' lifetime, except for fuel cell which has to be replaced every 20.000 operating hours. Annual real interest rate taken in the model was 6 %.

Table 1 shows considered input component parameters.

Table 1: Considered input component parameters

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

4. RESULTS

A feasible system is defined as a solution or hybrid system configuration that is capable of meeting the load. One system configuration (that includes all components) with a total of 249 combinations of size or number of components has been found feasible. Optimal system configuration with lowest total net present cost (138.452 €) is presented in Table 2. Levelised cost of energy for optimal system configuration is 2,901 €/kWh. Fig. 8 trough Fig. 11 show major components operating characteristics: hydrogen storage level, electrolyser power, fuel cell power and excess electricity, 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. 8). Unlike the fuel cell, electrolyser surprisingly operates 75% of operation time with its nominal power (Fig. 9).

Table 2: Optimal system configuration

Component	Size (kW)
Photovoltaic array	20
Wind turbine	10
Electrolyser	4
Power converter	4

Component	Size (kg)
Hydrogen tank	30

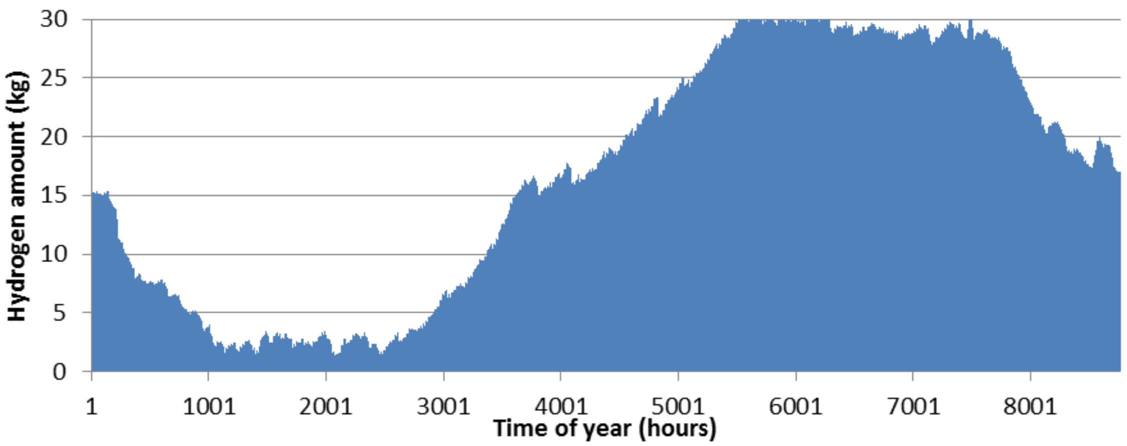

Fig. 7: Hydrogen tank storage level

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

Quantity	kWh/year	%
Excess electricity	12.655	47,5
Unmet electric load	0,0331	0,0
Capacity shortage	0,0331	0,0
Renewable fraction	/	100

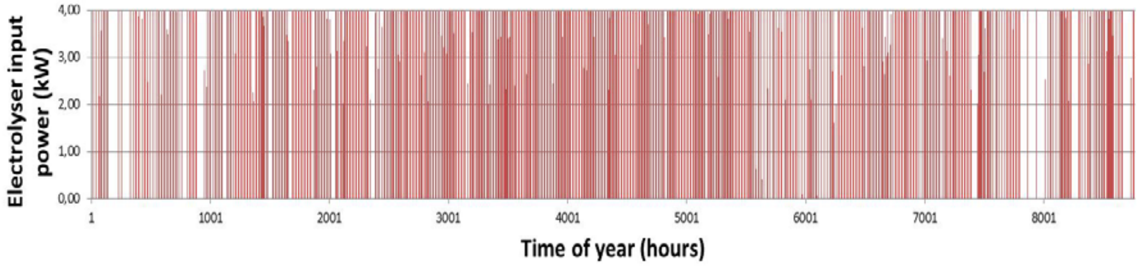

Fig. 8: Electroyser input power

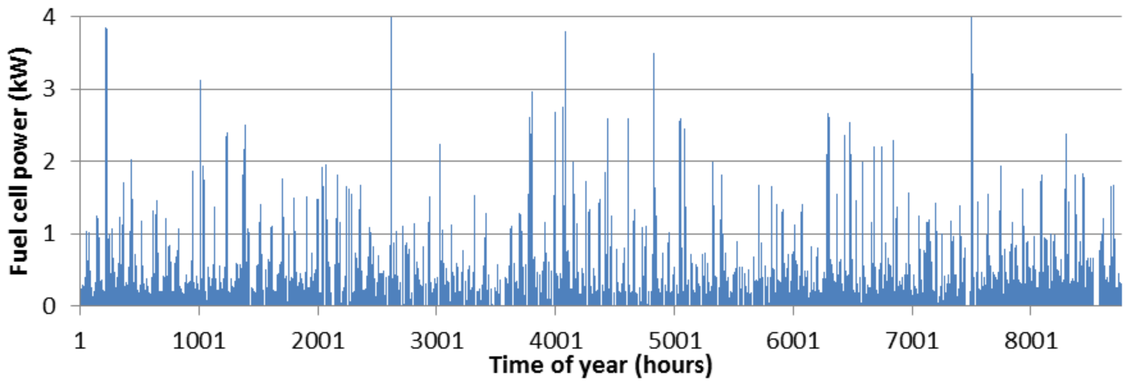

Fig. 9: Fuel cell output power

Table 4: Optimal system configuration characteristics

Quantity / Component	Unit	PV	WT	FC	EL	DC/AC
Rated capacity	kW	20,0	10,0	4,0	4,0	4,0
Mean output	kW (kg_{H2}*)	2,4	0,34	0,50	0,07*	0,47
Minimum output	kW (kg_{H2}*)	0,0	0,00	0,00	0,00*	0,13
Maximum output	kW (kg_{H2}*)	17,1	9,31	4,00	0,07*	3,8
Capacity factor	%	12,1	3,43	6,89	26,7	11,9
Component penetration	%	510	72,3	/	/	/
Hours of operation	hr/yr	3.873	3.556	4.834	2.500	8.760
Levelized cost	€/kWh (€/kg_{H2}*)	0,123	0,355	0,790	11,50*	0,038
Number of starts	starts/yr	/	/	523	395	/
Operational life	years	20	20	4,14	20	20
Fixed generation cost	€/hr	/	/	0,48	/	/
Hydrogen consumption/production	kg/yr	/	/	169	171	/
Specific hydrogen consumption/production	kg/kWh	/	/	0,070	0,018	/
Hydrogen energy input/output	kWh/yr	/	/	5.627	5.694	/
Mean electric efficiency	%	/	/	42,9	72	90

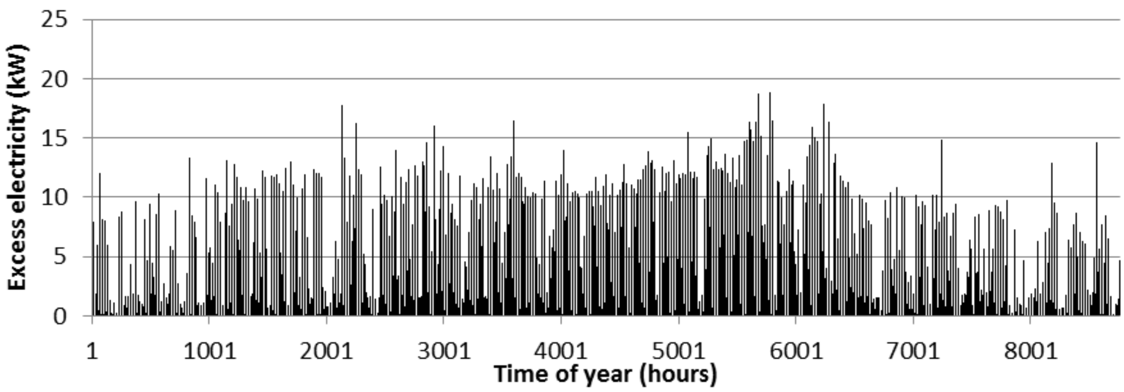

Fig. 10: Excess electricity from renewables

5. CONCLUSIONS

Numerical simulation with HOMER was based on:

- ARSO's reference year meteorological data,
- real household consumption measurements (project Mirabel)

- fuel cell fuel curve and electrolyser efficiency experimental values were used (acquired within CO NOT).

Based on simulation the following results were obtained:

- The 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.
- Hydrogen storage sub-system increases the value of RES as it successfully mitigates their intermittent and seasonal nature. It enables for smaller RES capacities to be installed.
- Nevertheless, due to low overall storage efficiency (30 %) the RES/hydrogen self-sufficient system still needs a relatively large nominal capacity (10-fold load peak power).
- Unlike most competitive storage technologies, hydrogen enables inter-seasonal storage.
- Large share (50%) of excess electricity can be used to supply heat load (electric water heating).
- Currently, if grid connection is available, RES/hydrogen stand-alone system is economically not competitive to grid purchased power. Total net present cost of 20 year electricity supply is 7.150 € (considering electricity specific cost to be 0,15 €/kWh), which is only 5 % of RES/H_2 system.
- Practical considerations also include large space requirements for such system installation: 200 m^2 of PV, many small or one relatively large wind turbine (12 m hub hight, 7 m rotor diameter), suitable space for hydrogen technologies installation and hydrogen container with 15 m^3 at 25 bar or 33 high pressure standard cylinders (50 L @ 200 bar).

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7. REFERENCES

[1] M. Tuma and M. Sekavčnik, *Energetski sistemi*, 3rd ed. Ljubljana: , 2004.

[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] 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 1,” *International Journal of Hydrogen Energy*, vol. 24, pp. 1139–1156, 1999.

[4] A. Pirc, B. Drobnič, M. Mori, and M. Sekavčnik, “Planning of a self-sufficient energy system with internal combustion enegine,” in *Power Engineering*, 2012.

[5] 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.

[6] 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.

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

[9] PEPESEC, “Energy planning for sustainable communities,” *Energy planning for sustainable communities*, 2010. [Online]. Available: http://www.cres.gr/pepesec/apotelesmata_uk.html. [Accessed: 10-Sep-2012].

[10] Slovenian Environment Agency, “Test reference year,” Ljubljana, 2008.

[11] National Renewable Energy Laboratory, “Getting Started Guide for Homer,” Golden, 2005.

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