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Application of a Hybrid Energy System Combining RES and H_2 in an Office Building in Lavrion Greece

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Abstract. In the framework of the H_2SusBuild project, a prototype hybrid energy system combining Renewable Energy Sources (RES) and hydrogen (H_2), as energy storage material and as a green fuel, has been designed, installed and is currently in operation in Lavrion, Greece. The system comprises thin-film PV panels, wind turbines, a water electrolysis unit, a H_2 compressor, a micro-CHP unit (PEM fuel cell) and a H_2 burner. The aim of this system is to cover the energy needs of a ≈500 m^2 office building and to render it a self-sustained, zero CO_2 emission installation.

The entire site is operated through an advanced Energy Management and Control System (EMCS), responsible for monitoring magnitudes of interest (for example power, energy, stored H_2 volume etc.) and managing the synergistic operation of all components based on a custom developed control algorithm. This paper's aim is to present the results of system operation and evaluate the performance of key components based on data collected during system operation under real conditions. The results show good efficiencies for all major system components and that the implemented control algorithm achieves the zero CO_2 emissions goal.

Key words

Hybrid energy system, RES, hydrogen, zero CO_2 building, system efficiencies

1. Introduction

The Building sector is a major contributor to Green House Gas (GHG) emissions as more than 40% of the total energy consumed in the EU is used to cover the needs for heating, cooling and electricity of buildings [1]. Given the EC objectives of reducing GHG emissions by 20% until year 2020 and increasing the share of renewable energy, there is a trend for the Building Sector to turn towards the use of RES. However, the inherent intermittent nature of the RES causes a temporal mismatch between electrical energy production and building energy demand profiles. In this frame, H_2 is examined both as an energy storage medium and as a green fuel. Its main advantages are the high energy density by mass and the fact that when burnt, the only by-product is water.

A literature search indicated that there are other attempts to develop synergistic systems between RES and H_2 either through the use of simulation [2], [3] or with application in real buildings [4], [5]. This paper presents the results from the development and operation of a RES-H_2 hybrid energy system during its application on a ≈500 m^2 office building located in Lavrion Technological and Cultural Park (LTCP), Greece.

2. System description

The RES-H_2 hybrid energy system consists of the following components:

1. 624 photovoltaic (PV) thin-film CIGS panels (total panel area 475 m^2, total installed power 46.8 kW) facing South at an angle of 23^0, connected to 6 SMA Sunny Mini Central 8000TL inverters (104 panels per inverter)
2. 6 downwind wind turbines (blade diameter 5.5 m, total installed power 36 kW) equipped with a flexible blade system, which allows the blades to pitch and cone in high wind speeds and a bearing assembly, which allows the rotor to self-orientate around 360^0, depending on wind direction and speed, connected to 6 SMA Windy Boy 6000A inverters
3. water electrolysis (EL) unit (22.3 kW) to produce gaseous H_2 (max production capacity 4 Nm^3/h at 12 bar) with remote operation capability through Ethernet connection
4. H_2 distribution grid (piping made from 316 stainless steel) and H_2 storage vessels (4 bundles

of Type I vessels, max water capacity 3480 lt, max working pressure 200 bar)

5. H_2 compressor to enable the gaseous H_2 storage in high pressure (up to 200 bar) with remote operation capability
6. micro-CHP PEM Fuel Cell (FC) (20 kWel and 20 kWth) with peripherals (air blower, water deionization system, control cabinet, DC to AC inverter etc.) to convert the stored H_2 to electrical and thermal energy
7. prototype H_2 burner with a condensing boiler (60 kWth) to convert the stored H_2 to thermal energy
8. Heat Recovery System (HRS) to exploit the thermal energy produced by the FC and the H_2 burner
9. Energy Management and Control System (EMCS) to control the flow of energy by managing RES and control devices, to monitor system operation, to maximize efficiency and to ensure reliability in system operation
10. Safety and Protection System (SPS), to guarantee the safety of the installation and the occupants of the building.

A. Building

The building's overall dimensions are 30.50 m x 15.50 m, divided in two floors (ground floor of 375 m^2 and attic of 150 m^2). The ground floor consists of a waiting area, a small kitchen, WCs, the control room and the main area while the attic floor consists of a waiting area, two offices and a conference room.

The equipment responsible for the generation, storage and consumption of H_2 is housed in a completely isolated area of the building named GenConStore area (Figure 1). This area consists of three 5 m x 5 m rooms all with 60 min fire resistant walls and doors. A separate ventilation system guarantees fresh air recirculation (6 air changes per hour) during equipment operation.

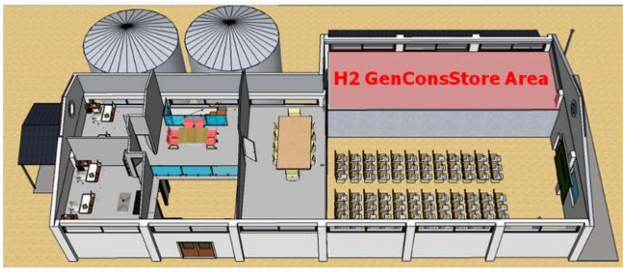

Figure 1. 3D cut-out view of the demonstration building.

B. EMCS

The EMCS consists of two sub-systems, the monitoring system and the control system. The monitoring sub-system is using smart metering devices to measure and store the values of selected parameters based on the Modbus protocol. A total of 24 devices are used so that the building loads can be separated according to type and location. The measurements are fed to the control sub-system that incorporates the full-scale plant control algorithm according to which the operation of equipment and flow of energy are managed (Figure 2). All measurements are recorded and stored in a database in 1 min intervals.

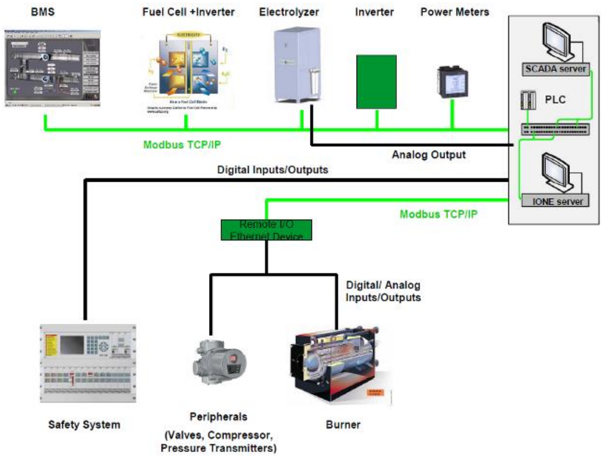

Figure 2. Architecture of the control sub-system of the EMCS.

The implemented logic of the RES-H_2 system operation is based on the balance between the energy produced and the energy consumed. The calculation of this balance is performed in 5 min intervals and depending on the result, the appropriate commands are issued. The goal is to use the electrolyser to produce and store H_2 when there is a surplus of energy and to use the FC and/or H_2 burner to produce electrical and/or thermal energy when there is a shortage of energy in the system. In this way, the primary objective of the control algorithm is to achieve a Zero Energy Building (ZEB), thus resulting in zero energy exchange with the public power grid and zero CO_2 emissions.

The plant operator(s) can interact with the EMCS through a developed GUI that provides a unified interface for, almost real-time, system operational status monitoring and control (Figure 3). The most important measurements representing the actual flow of energy in the system as well as the most critical equipment operational parameters can be seen and controlled in one screen thus providing increased functionality and ease-of-use.

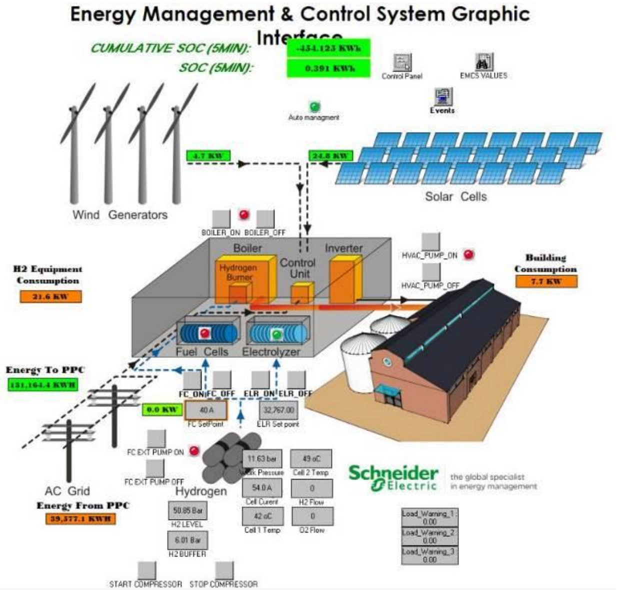

Figure 3. Developed GUI for the EMCS.

C. SPS

The SPS manages signals that are collected from different types of detectors placed inside the

GenConStore area (H_2 detectors to check for leakages, IR flame detectors, smoke detectors, electromagnetic isolation valves, heat sensors, inert gas (N_2) extinguishing system, audiovisual alarms) and integrates safety measures and procedures that are initiated in case of alarm.

In case that any of the detectors is triggered and an alarm occurs, the SPS will inform predefined recipients and depending on the type of alarm a series of pre-configured procedures will be activated. These procedures include (but are not limited to) the isolation of the H_2 distribution grid and storage cylinders using the electromagnetic valves, the termination of equipment operation, the activation of the fire extinguishing system etc.

The initial evaluation for the dimensioning of the system components was based on simulating the building energy consumption using commercial software packages (TRNSYS). In combination with historical meteorological data, the simulation results were used to identify the proper RES installed power and subsequently, the rest of the H_2 system components basic parameters.

3. Performance evaluation results

The performance evaluation was executed by conducting energy balances on every system component in order to calculate the associated efficiency. The calculations were performed using measurements under real operating conditions and the results are presented for each component separately. All data, except from the RES, refer to the period from February to September 2012. RES data refer to the whole year of 2011 to account for seasonal weather variations.

D. RES

1) PV panels

There are three performance parameters that are used to define the overall system performance for PV systems. These parameters are the final PV system yield, reference yield and performance ratio. The final PV system yield (Y_f) is the net energy output E divided by the nameplate DC power P_o of the installed PV array (Equation 1).

$$Y_f = \frac{E}{P_o} \tag{1}$$

In Equation 1, E is directly measured by the EMCS monitoring subsystem while P_0 is known from the panel specifications.

The reference yield (Y_r) is the total in-plane irradiance H divided by the PV's reference irradiance G (in the case of the project's installed PV panels, G refers to the Standard Test Conditions and is equal to 1000 W/m^2) (Equation 2).

$$Y_r = \frac{H}{G} \tag{2}$$

In Equation 2, H is directly measured (along with other meteorological data) using a Davis Vantage Pro2 weather station.

The performance ratio (PR) is the Y_f divided by the Y_r (Equation 3). Since PR normalizes with respect to irradiance, it quantifies the overall effect of losses due to inverters and wiring, PV panel temperature, soiling or snow, system downtime and component failure.

$$PR = \frac{Y_f}{Y_r} \tag{3}$$

Since all magnitudes are known, Y_f, Y_r and PR can be easily calculated.

The yearly system yield (Y_f) is 1463.51 kWh/kW, which is above average for the area of Attica in Greece (approximately 1300 – 1400 kWh/kW [6]). The yearly reference yield (Yr) is 1899.30 and the performance ratio (PR) is 77.06%. Total energy production during 2011 was 68492.34 kWh.

Figure 4 depicts the energy production per inverter and per month for 2011.

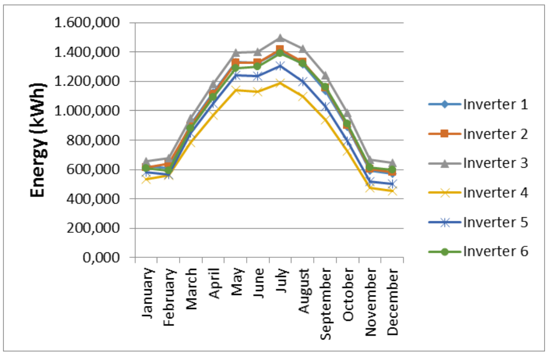

Figure 4. Energy produced per inverter of the PV system for 2011.

It should be noted that soiling (dust accumulation) was found to be the most detrimental factor concerning energy production from the PV system. This phenomenon was particularly observed after periods of strong winds or long periods without rain. A periodic cleaning procedure was implemented to deal with this problem.

2) Wind Turbines

In the case of the wind turbines the performance evaluation focused on calculating the system yield and the energy production (following a similar procedure as for the PV panels).

Therefore, the system yield of the wind turbines is calculated equal to 1139.82 kWh/kW and total energy production was 41033.67 kWh.

Figure 5 depicts the energy production per inverter and per month for 2011.

As can be seen, there are variations in the energy production between the wind turbines (the difference between the highest and lowest performing one is close to 35%). This is attributed to the varying topomorphy of the landscape where the wind turbines are installed (hill approximately 50 m from the building), resulting in each of the wind turbines to be exposed to different wind speed and direction profiles.

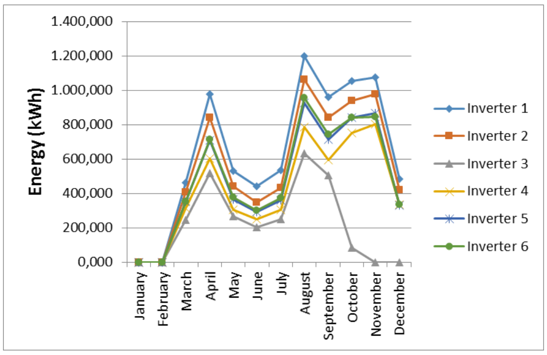

Figure 5. Energy produced per inverter of the WT system for 2011.

The zero energy production from wind turbine no 3 towards the end of 2011, is due to increased wear on its main shaft bearing assembly that led to the turbine being stopped in order to avoid further damage until repairs could be completed.

E. Building

Building operation is constantly managed by an installed BMS according to office usage profile regarding temperature setpoints and lighting operation. The basic scheme is outlined below:

- Building lights turn on at 08:00 and turn off at 18:00
- HVAC turns on at 09:00 and turns off at 17:00
- Interior temperature setpoint is 21 ºC (heating mode) and 26 ºC (cooling mode)
- All consumptions are off during Saturdays and Sundays (except of course from the EMCS and SPS)

However, it should be taken in consideration that in case of energy shortage the EMCS can apply load balancing schemes to save energy.

Using the EMCS monitoring sub-system, the building's annual total energy consumption was calculated approximately equal to 69000 kWh. Since the total surface area is 525 m^2 the average building energy consumption is calculated approximately equal to 131.4 kWh/m^2/year. Total energy consumption is distributed as follows: 64% towards HVAC, 14% towards lighting and the remaining 22% towards office equipment (Figure 6).

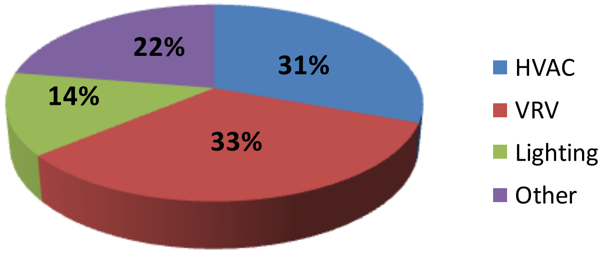

Figure 6. Energy consumption distribution according to building load type.

By comparing the annual RES energy production and the annual building energy consumption, it is clear that there is a 40000 kWh energy surplus that is available for the production of gaseous H_2.

The building's total power consumption profile for a period of 4 months is presented in Figure 7. As expected, the building's power consumption profile is largely dependent on the ambient conditions and seasonal changes as there is a distinctive drop in maximum load from March to April.

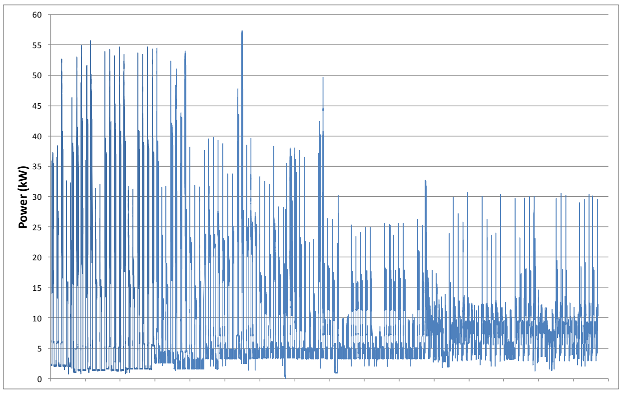

Figure 7. Building's total power consumption profile.

Depending on the season of the year the average building load varies between 6.5–10 kW and the max building load varies between 30–57 kW. This variation is mainly due to the different operation of the building's HVAC systems.

A peak power profile analysis has also been conducted so as to identify the peak load of the building as a whole as well as the duration for which this load occurs. Using the detailed consumption profile of the entire building, the analysis first calculated the building's average power consumption, on a monthly basis. Subsequently, any consumption that was higher than this average was characterized as a "peak". The duration of the peak was defined as the time period during which the load remained higher than the average. The results of this analysis are shown in Table 1.

Table 1. Peak power profile analysis statistics.

Month	**Average building load (kW)**	**Maximum peak building load (kW)**	**Average Peak Duration (min)**
February	10.070	55.750	7.900
March	9.400	57.450	18.954
April	6.560	49.730	61.687
May	7.400	30.640	17.994
June	8.734	36.640	26.101
July	9.860	43.200	14.740
August	7.665	32.740	38.141
September	6.470	32.360	13.384

F. Electrolyser

In order to evaluate the performance of the electrolyser, different operation cycles were considered in order to calculate magnitudes such as the average and maximum power consumed, total energy consumed, quantity of produced H_2, specific yield and energy efficiency.

The power and energy are directly measured by the EMCS, while the quantity of produced H_2 is calculated using the pressure change in the storage. The specific yield is calculated as the ratio of the energy consumed to the quantity of H_2 produced (Equation 4).

$$Specific\ Yield = \frac{E_{consumed}}{V_{H2produced}} \tag{4}$$

The energy efficiency is defined as the ratio of the total electrical energy that it is consumed to the energy that is contained in the produced H_2. The latter is calculated using the High Heating Value (HHV = 12.7 MJ/m^3) (Equation 5).

$$Efficiency = \frac{E_{H2}}{E_{consumed}} \tag{5}$$

The results for two different operational cycles of the electrolyser are shown in Table 2.

Table 2. Electrolyser operation results.

Average power consumed (kW)	Energy consumed (kWh)	H_2 produced (Nm^3)	Specific yield (kWh/Nm^3)	Efficiency (%)
19.987	99.946	14.752	6.775	52.069
19.923	74.788	11.075	6.753	52.242

The electrolyser's specific yield was calculated equal to 6.78 kWh/Nm^3 of produced H_2, while the average and maximum power consumption were 20 kW and 24.5 kW respectively. The energy efficiency of the EL was found equal to approximately 52%.

Another important characteristic is the time that the EL needs from starting operation until it achieves maximum production rate, which was calculated at 2 mins.

G. H_2 Compressor

The goal of the performance evaluation was to determine the average and maximum power consumption, the specific energy consumption as well as the average and maximum compressor capacity (i.e. compression rate).

In order to calculate the latter, the rate of H_2 pressure change in the storage was used. The specific energy consumption is defined as the ratio of the total energy consumed to the total volume of compressed H_2 (Equation 6).

$$Specific\ Consumption = \frac{E_{consumed}}{V_{H2compressed}} \tag{6}$$

The results for two different operational cycles of the compressor are shown in Table 3.

Table 3. Compressor operation results.

Average power consumed (kW)	Energy consumed (kWh)	H_2 compressed (Nm^3)	Specific energy (kWh/Nm^3)	Average compressor capacity (Nm^3/h)
1.454	8.823	15.799	0.558	2.619
1.467	11.437	20.264	0.564	2.592

The H_2 compressor consumes about 0.56 kWh/Nm^3 of compressed H_2 at an average compression rate of 2.60 Nm^3/h. Maximum power consumption is approximately 2.6 kW.

It must be noted that the actual compressor capacity is determined according to the actual production rate of the electrolyser (Figure 8).

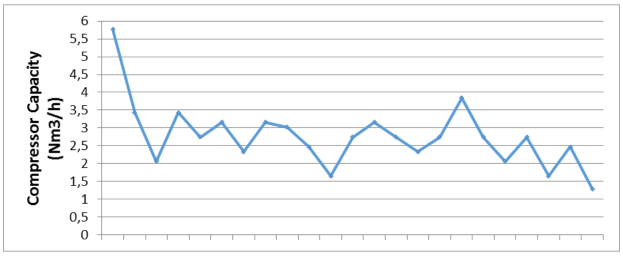

Figure 8. Compressor capacity vs time.

H. Micro-CHP Fuel Cell

The goal of the performance analysis was to determine the H_2 consumption as well as the electrical and thermal energy production and efficiencies of the micro-CHP FC. However, additional performance criteria were calculated such as the response times needed from start of operation until energy is fed to the building and from start of operation until maximum power is achieved.

In similar context to the previous components' analyses the H_2 consumption is calculated using the pressure changes inside the storage vessels.

The electrical energy that is produced is directly measured by the EMCS, while the thermal energy is calculated by the temperature increase of the water that is used to cool the FC (Equation 7).

$$E_{produced\ FC\,Th} = m * c_p * \Delta T \tag{7}$$

, where m is the mass of water, c_p the water specific heat and ΔT the temperature increase.

The specific yield ratio is defined as the ratio of the net electrical energy produced (since a small portion is used by the FC itself) to the energy that is contained in the consumed H_2 (Equation 8).

$$Specific\ Yield = \frac{E_{produced\ FC\,Elec} - E_{consumed\ FC}}{V_{consumed\ H2FC\,total}} \tag{8}$$

Finally, the calculation of the electrical and thermal efficiencies were performed based on Equations 9 and 10 respectively.

$$Efficiency_{Elec} = \frac{E_{produced\ FC\,Elec} - E_{consumed\ FC}}{E_{H2}} \tag{9}$$

$$Efficiency_{Th} = \frac{E_{produced\ FC\,Th}}{E_{H2}} \tag{10}$$

The results for two different operational cycles of the compressor are shown in Tables 4a and 4b.

Table 4a. Micro-CHP FC operation results.

Energy consumed (kWh)	Electrical energy produced (kWh)	Thermal energy produced (kWh)
0.002	7.659	7.461
0.002	8.385	8.153

Table 4b. Micro-CHP FC operation results.

H_2 consumed (Nm^3)	Specific yield (kWh/Nm^3)	Electrical efficiency (%)	Thermal efficiency (%)
4.635	1.652	46.826	45.630
5.149	1.628	46.149	44.884

The specific electrical energy production of the micro-CHP unit is 1.64 kWh/Nm^3 of consumed H_2. The electrical and thermal efficiencies are 46% and 45% respectively (total efficiency 91%). The H_2 consumption is equal to 5 Nm^3/h during operation at 10 kW power and scales almost linearly for higher power levels.

Figure 9 presents the electrical power produced by the FC versus time during a typical operation cycle. The starting point of this Figure matches the time when the EMCS gives the command to the FC to start operation. As can be seen, the FC needs about 3 mins from operation start until electrical energy is fed to the building and a total of 5 mins to achieve the maximum power level.

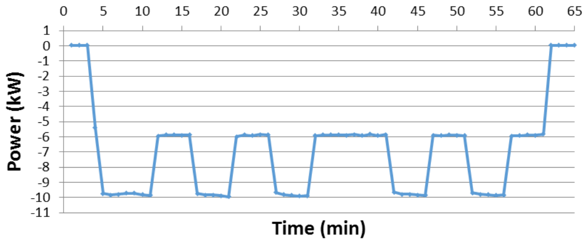

Figure 9. Produced electrical power vs time during typical FC operation.

The observed power production pattern that involves changes at the power setpoint of the FC is determined by the commands issued from the EMCS according to the balance of energy in the entire system. When the energy shortage becomes higher (i.e. more energy is needed to achieve equilibrium) the FC has to operate at a higher setpoint and vice-versa.

I. Energy exchange with the grid

The primary objective of the developed RES-H_2 hybrid energy system was to achieve the ZEB target. In other words, the energy exchange with the grid should ideally be zero (the amount of electrical energy that is taken from the grid should be equal to the amount of energy that is given to the grid). Table 5 presents these data on a monthly basis for the entire full-scale demonstration plant (building, H_2 equipment and peripherals).

Table 5. Energy exchange between demonstration plant and public power grid.

Month	Energy given to PPC (kWh)	Energy taken from PPC (kWh)	Difference (kWh)
March	3153.70	3922.42	-768.72
April	2779.26	3535.01	-755.75
May	2432.40	4967.30	-2534.90
June	3524.00	2514.10	1009.90
July	2951.80	3112.07	-160.27
August	3734.39	1965.18	1769.21
September	2891.28	2950.98	-59.70
October	2208.92	2205.62	3.30
TOTAL	**23675.75**	**25172.68**	**-1496.93**

As can be seen, taking into consideration the entire period the system is very close to achieving the ZEB target. This is also supported by examining July, September and October of 2012 individually, during which the energy exchange with the grid is minimal and almost zero.

4. Conclusions

Based on the above results as well as the experiences gained from daily operation of the installation, the following conclusions can be drawn regarding the developed RES-H_2 hybrid energy system:

- The system has been successfully implemented in a medium-sized office building.
- No safety problems have occurred since system start-up and commissioning.
- Compared to the relevant literature, the equipment calculated efficiencies can be characterized as good.
- The developed control algorithm helps the building to achieve the zero CO_2 emissions goal.

In the future, a techno-economic evaluation of the installation with data concerning installation, operation and maintenance costs will be carried out in order to determine and formulate a feasible exploitation strategy.

Acknowledgement

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