Hydrogen and renewable energy sources integrated system for greenhouse heating

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Abstract

A research is under development at the Department of Agro-Environmental Sciences of the University of Bari "Aldo Moro" in order to investigate the suitable solutions of a power system based on solar energy (photovoltaic) and hydrogen, integrated with a geothermal heat pump for powering a self sustained heated greenhouse. The electrical energy for heat pump operation is provided by a purpose-built array of solar photovoltaic modules, which supplies also a water electrolyser system controlled by embedded pc; the generated dry hydrogen gas is conserved in suitable pressured storage tank. The hydrogen is used to produce electricity in a fuel cell in order to meet the above mentioned heat pump power demand when the photovoltaic system is inactive during winter night-time or the solar radiation level is insufficient to meet the electrical demand. The present work reports some theoretical and observed data about the electrolyzer operation. Indeed the electrolyzer has required particular attention because during the experimental tests it did not show a stable operation and it was registered a performance not properly consistent with the predicted performance by means of the theoretical study.

Introduction

Advanced greenhouses mainly need heating systems, in addition to electrical energy for ventilation, irrigation and fertilization. In detail, in horticultural and floricultural context, winter heating for green-houses can be the 70% of production costs, being often a limit to an optimal vegetative development of protected crops for unsustainable costs (Scarascia Mugnozza G. et Anifantis A., 2009).

The use of suitable microclimate control systems, energy efficiency strategies and renewable energy sources could provide a significant impetus for greenhouse gases reduction and contribute reaching legislated energetic and environmental targets and improving the environmental performance of the greenhouses (Scarascia Mugnozza *et al*., 2011), ensuring at the same time optimal microclimate conditions for protected crops (Ozgener *et al*., 2005).

Geothermal heat pumps potentiality in the agricultural sector and especially for greenhouse heating demands have been successfully estimated (Dickson *et al*., 2004); in these circumstances heating plants are economically advantageous having a low environmental impact too (Benli, 2013; Chai *et al*., 2012; Scarascia Mugnozza *et al*., 2011; Ozgener, 2010; Kondili et Kaldellis, 2006; Adaro *et al*., 1999).

The urgent need to pass from conventional energetic systems, based on fossil fuel resources, towards energetic systems based on solar and wind energy, has to face the problems related to variable and unpredictable energy availability from renewable sources. Consequently it is necessary to provide this systems with a power back up arrangement as in example batteries, which are commonly used for this purpose but have also some limitations such as limited lifetime and low energy storage capacity. Fuel cells application, fuelled with hydrogen, is better than batteries when used to support solar energy power plants (Ro et Rahman, 1998).

Renewable sources energy can be used to generate high purity hydrogen gas through water electrolysis process; produced hydrogen, as energy vector, can serve to store energy produced in excess when compared to demand, and at a later stage it can be used as a fuel to reproduce electricity through fuel cell systems.

At present a lot of researches have been carried out and are still being developed on modelling, analysing and optimization of solar (photovoltaic and wind)-electrolyzer-fuel cell hybrid power systems with backup consisting in hydrogen storage systems (Khan et Iqbal, 2005; Jallouli et Krichen, 2012) with the hydrogen stored as liquid, as gas under pressure or through metal hydrides (Miland et Ulleberg, 2012); such researches sustain feasibility and reliability of solar hydrogen power systems.

However few studies have been done regarding the integration of solar hydrogen power systems with greenhouses, supporting that these systems provide a viable option for powering stand-alone greenhouse in a self-sustained manner (Ganguly *et al*., 2010).

Therefore a research is under development at the Department of Agro-Environmental Sciences of the University of Bari "Aldo Moro" in order to investigate the suitable solutions of a power system based on solar energy (photovoltaic) and hydrogen, integrated with a geothermal heat pump for powering a self sustained heated greenhouse. The present work reports some theoretical and observed data about the electrolyzer operation.

Materials and methods

The experimental greenhouse

The experimental study was carried out at the experimental farm University of Bari sited in Valenzano (Bari, Southern Italy), latitude 41° N. A greenhouse-integrated system composed of photovoltaic panels, electrolyser bank, Polymer Electrolyte Membrane fuel cell stacks and a geothermal heat pump was set up.

A system of equipments have been designed and installed in order to produce electricity from solar photovoltaic source (PV) and hydrogen gas from water by means of an electrolyser powered by PV. The produced hydrogen is stored in a pressure tank and than it is used as fuel by a fuel cell system producing electricity for greenhouse energy demands when photovoltaic is inactive (during night time or overcast sky).

The electrical energy produced was used for powering the heating system set in order to satisfy the thermal energy demand of 48 m^2 double plastic skin greenhouse; therefore the use of renewable energy was combined with passive techniques of energy saving using an inflated double film for increasing thermal transmittance.

The main structure of the greenhouse, arched roof one, is made of tubular galvanized steel. The coverage is made of a double ethylene vinyl acetate film (multiEVA 33 AD AF), each one having a thickness of 200 m, with an interposed 2 cm air space, which is kept under constant pressure by an air pump. The base and the warheads (east and west-facing greenhouse surface) are corrugated sheets made of polyester reinforced with glass fibers (PRFV). Each greenhouse is provided with a sliding door, a vertical fan/air extractor and an air inlet louver, all of which are placed on a single warhead.

Another greenhouse unheated, with the same geometric and constructive characteristics, has been realized for comparison (Figure 1).

The two greenhouses are east-west oriented, being 8 m in length and 6 m in width, 3.5 m in height. Therefore the surface coverage is about 120 m^2 and the volume is about 150 m^3.

The distance between the two greenhouses is 12 m; therefore there is no mutual shading.

The necessary heating power Q_H was evaluated using the heat balance with the main power losses between the air inside the greenhouse and the external ambient. Thus Q_H was calculated by means of the following equation (1):

$$Q_H = Q_c + Q_v + Q_i \qquad [W] \qquad (1)$$

where:
Q_c is the conduction and convection power loss through the greenhouse covering system [W];
Q_v is the inside air leakage power loss between the internal and external ambient [W];
Q_i is the power loss by radiation from covering film to blue sky [W].

The greenhouse heating system was realized through black plastic hose supplied by a 7.2 kW low-enthalpy geothermal heat pump equipped with 120 m vertical double U-bend ground heat exchangers.

The hybrid system

The power plant has been designed with the purpose of using the photovoltaic production also directly, avoiding the double energy conversion involving energy losses (electricity hydrogen electricity) when there is simultaneity between photovoltaic energy production and greenhouse energy demands. The designed passive loads are seasonally dependent.

The system (Figure 2) can be powered through the national electric

grid in order to guarantee always the energy supply in case of default of the power system.

The whole energy system, except for PV modules and storage tanks, is enclosed in a steel cabinet (Figure 3) subdivided into two separate chambers, one encloses the process unit, the second one encloses the power supply unit. The process unit contains all equipment, piping and field instruments necessary for carrying out the water electrolysis process, and also the fuel cells.

The array of photovoltaic panels consists of 24 modules of 240 W peak power, maximum operating voltage 29.64 V. Modules were grouped in two series, grouped in parallel, in order to achieve a nominal voltage of the array of 360 V. The PV modules have a total area around 39 m^2, south-oriented with an elevation angle of 30° in order to maximize annual energy production (Figure 4). The PV modules have been set up on a tubular galvanized steel structure.
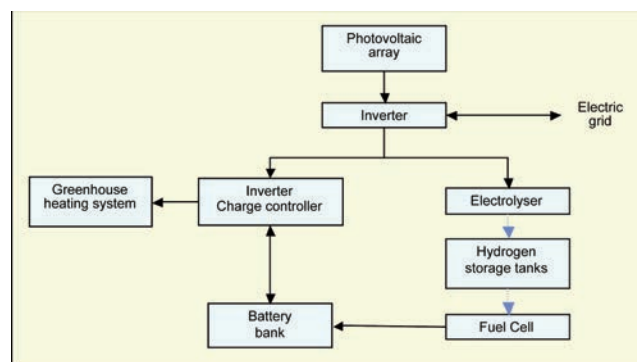

Figure 1. Experimental greenhouses.

Figure 2. Functional diagram of the power plant.

Figure 3. Plant external layout.

The renewable energy produced by the aforesaid PV modules was converted to AC power by an inverter in order to feed the water electrolyser sited in the cabinet. Furthermore the AC power could also feed the grid. The inverter has an input voltage of 300-600 VDC and an output AC voltage of 230 VAC.

The electrolyser unit has an input voltage of 230 VAC and its consumption is of 3.55 kW. The hydrogen nominal production rate (dry gas) is 0.4 Nm^3/h with output pressure of 3 MPa. Moreover the hydrogen production rate is directly proportional to the AC flow set to be conducted along the cell stack. It has been chosen to add Potassium Hydroxide (KOH 28%) to the contained water for forming the electrolyte, in order to make it highly conductive.

The produced hydrogen is stored under pressure at 3 MPa in two steel tanks of 0.6 m^3 placed outside the cabinet (Figure 3). The fuel cell system is based on the proton exchange membrane (PEM) technology and is set in the process unit of the cabinet; it is designed with modular cartridge technology, having a peak power of 2 kW.

The fuel cell requires industrial grade hydrogen (99.95%) and oxygen (air) and has as by-products pure water/vapor and heat; the output voltage is of 48 VDC and the consumption is of 30 standard liter per minute (slpm) at 2 kW (operation temperatures 0°C÷ 46 °C).

The energy produced by the fuel cells is used to charge a battery bank consisting of six 12V cells connected in series and in parallel providing a global energy of 900 Ah.

Finally an inverter is connected to the battery terminals in order to be used as a stand-alone sinusoidal AC voltage provider.

The system monitoring and control, placed in the control unit, is based on a programmable logic controller (PLC) and is integrated with a power supply unit. The PLC manages all the processes and safety.

This system has been set up and it has been finished in April 2013. During the month of May 2013 operation tests have been carried out paying attention on the functionality of the electrolyzer; the amount of hydrogen produced was evaluated during daytime hours of different days.

Theoretical considerations concerning the electrolyzer

According to Faraday's law, the production rate of hydrogen M_{elec} in a water electrolyzer, consisting of a certain number of electrolyzer cells connected in series, can be calculated by (Li *et al*., 2009):

$$M_{elec} = \eta_F \; x \; N_{elec} \; x \; I_{elec} \, /(n \; x \; F) \qquad [\text{mol s}^{-1}] \qquad (2)$$

where:
η_F is the Faraday efficiency;
N_{elec} is the number of electrolyzer cells in series;
I_{elec} is the current through the electrolyzer [A];
n is the number of moles of electrons per mole of water, $n = 2$;
F is the Faraday constant (96487 C mol^{-1}).

The Faraday efficiency, that is often called the "current efficiency", is defined as the ratio between the actual and the theoretical maximum amount of hydrogen produced in the electrolyzer (Ulleberg, 2003).

According to the manufacturer of the electrolyzer the value of $_F$ is equal to 91%.

To produce hydrogen the working voltage U (V) between the two electrodes must be higher than the minimum decomposition voltage U_{tn}:

$$U_{tn} = \Delta H \, / \, nF \qquad [\text{V}] \qquad (3)$$

where:
ΔH is the standard enthalpy for splitting water of hydrogen [286 kJ mol^{-1}];

$n = 2$.

At standard conditions U_{tn} = *1.482 V* (Ulleberg, 1998).

The voltage efficiency η_V is defined by:

$$_V = U_{tn} \, / \, U \qquad [\%] \qquad (4)$$

According to the manufacturer of the electrolyzer the value of $_V$ is equal to 80%.

Considering the registered values of the working voltage of the experimental electrolyzer, the η_V can be calculated by means of eq. 4; thus the actual voltage efficiency η_V will be 75%.

The power consumption of an electrolyzer can be expressed as (Li *et al*., 2009):

$$P_{elec} = I_{elec} \; x \; U \; x \; N_{elec} \qquad [\text{W}] \qquad (5)$$

Thus the hydrogen production by the electrolyzer, taking into account equation 2, can be calculated as:

$$M_{elec} = \eta_F \; x \; P_{elec} \, / \, (\; U \; x \; n \; x \; F \;) \qquad [\text{mol s}^{-1}] \qquad (6)$$

Considering the registered values of the hydrogen production, the power consumption and the working voltage of the experimental electrolyzer, the Faraday efficiency η_F can be calculated by means of eq. 6; thus the actual voltage efficiency η_F will be 87%.

The electrolyzer unit has a built-in gas compressor in order to store the produced hydrogen in tanks. The power necessary to compress the gas can be calculated by (Li *et al*., 2009):

$$W_c = m_c \; x \; C_p \; x \; T_1 \; x \; (1/\eta_c) \; x \; [(P_2/P_1)^{(r-1)/r} \, \text{-}1] \qquad [\text{W}] \qquad (7)$$

where:
m_c is the flow rate of hydrogen through the compressor [kg s^{-1}];
C_p is the specific heat oh hydrogen at constant pressure (14304 kJ (kg K)$^{-1}$);
T_1 is the inlet gas temperature of the hydrogen compressor (313.15 K);
η_c is the isentropic efficiency of the compressor [%];
P_2 is the output gas pressure of the hydrogen compressor (3 MPa);
P_1 is the inlet gas pressure of the hydrogen compressor (0.6 MPa);
r is the isentropic exponent of hydrogen (1.4).

The mole mass of hydrogen is 2.016 (g mol^{-1}); therefore $m_c = M_{elec} \; x$ *2.016 / 1000 (kg s^{-1})*. The value of η_c in this work is assumed equal to 68% according to manufacture data.

Figure 4. The photovoltaic array.

Results and discussion

Figure 5 shows the photovoltaic electrical production (kW) as a function of the hour during a day of May 2013; this day was characterized by a highly variable weather similarly to the other days of the month and then the evaluated day can be considered representative for May 2013. The electrolyzer started to produce hydrogen when the photovoltaic production was greater than 1.6 kW, that is in the periods 8-10 and 11-14. Figure 6 shows through a dashed line the amount of produced hydrogen as a function of the stack power consumption. These experimental data are compared, in the same Figure, with data (through a continuous line) calculated by means of equation 6.

According to the experimental data aηnd by means of theoretical considerations (Figure 6), we have assessed the actual voltage efficiency ($\eta_V = 75\%$) and the actual Faraday efficiency ($\eta_F = 87\%$) which are clearly lower than the manufacturer efficiency values. The actual production of hydrogen is slightly different from the calculated one obtained by means of theoretical conditions (Figure 6).

These disagreements between expected and registered values are probably due to the mathematical model. Effectively this model contemplates electrolyser working at atmospheric pressure and at constant temperature. Furthermore the compression of the hydrogen (equation 7) takes place after its production in suitable compressor.

The realized electrolyzer besides works under pressure of 0.3 MPa with a changeable operative temperature (20 °C-80 °C) and the produced hydrogen is already pressed (0.3 MPa), ready to be stored in the tanks. Consequently the power necessary to compress the hydrogen is secondary if compared to the one related to the theoretical model (equation 7).
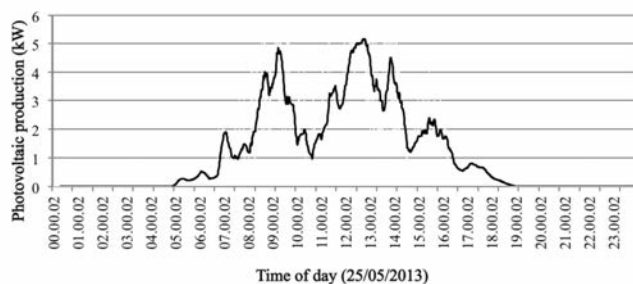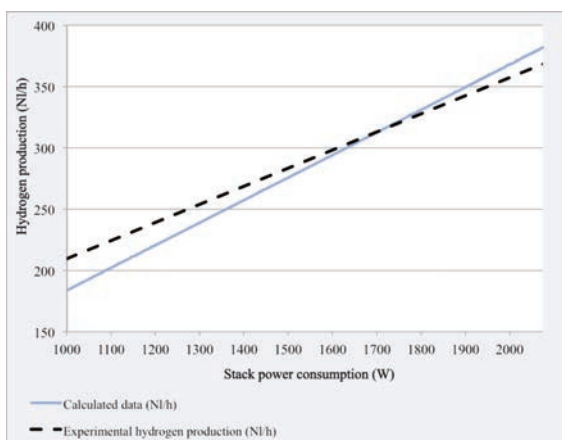

Figure 5. The daily photovoltaic production

Figure 6. The hydrogen production.

Conclusions

The realized system has required the analysis of different technical characteristics related to the heating demands of the experimental greenhouse, the ground source heat pump, the hydrogen production, the storing system, the photovoltaic system. Further studies have been carried out to evaluate the connection and the affects among the members in order to obtain a hybrid system for the production and storing of green hydrogen. Above all the electrolyzer has required particular attention because during the experimental tests it did not show a stable operation and it was registered a performance not consistent with the predicted performance by means of the theoretical study. Some technical operations are being carried out for enhancing the system functionality, making it suitable to the designed task of supplying electrically the greenhouse heating system during cold periods.

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