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Energy storage solutions for small and medium-sized self-sufficient alternative energy objects

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Energy storage becomes more important as mankind switch to renewable energy, away from fossil resources. Traditional way – batteries - offer a limited number of cycles, require regular maintenance; nevertheless gravitational storage, flywheels, compressed air are mainly large scale and expensive methods. The hydrogen as energy carrier and hydrogen fuel cells are possible option to store different amounts of energy for relatively long times with low losses. Different solutions for self-sufficient sun/wind energy objects are analysed - the solar radiation collecting systems, wind power generators, and high pressure electrolysis technologies for hydrogen production and the metal-hydride energy storage. This article describes the development of a versatile technology that can be used to provide continuous power for small and medium-sized self-sufficient objects or their micro-grids using alternative energy and energy storage. The technology uses advanced electrolysis and fuel cells to efficiently store excess energy from sun/wind generation as hydrogen for later use in fuel cells.

Keywords: Energy storage, metal-hydride, electrolysis technologies

INTRODUCTION

In order to reduce greenhouse gas emissions within the European Community and reduce its dependence on energy imports, the development of energy from renewable sources should be actively supported. The Renewable Energy Directive [1] establishes an overall policy for the production and promotion of energy from renewable sources and requires the EU to fulfil at least 20% of its total energy needs with renewables by 2020 – to be achieved through the attainment of individual national targets. Improvement the efficiency of wind energy infrastructure and solar energy sector using hydrogen as energy carrier storage technologies will significantly reduce the consumption of hydrocarbon fuels and will improve the environment in the most environmentally stressed urban areas and industrial regions.

Implementation of renewable energy solutions is essential in Latvia and Ukraine too. Latvia is depending on energy imports –deficit of electricity (12-33%); shortages in heat production resources (55-70%) and the lack of 99% of local fuel for transport [2]. For production of electricity and heat in Latvia, imported (natural gas, coal, fuel oil) and local (vegetable oil, alcohol, wood) resources are used after business interests of neighbourhood big companies. Energy resources for district heating in Latvian cities are mainly imported (coal, coke, petroleum products, natural gas) and only 30% are local (used tires, waste, peat, wood, charcoal, straw, wood, biogas, bioethanol, biodiesel, hydropower, wind energy). It is possible to reduce the energy sector's dependence on import in Latvia by switching to local renewable energy resources - sun, wind, rivers, biomass, geothermal, but the transport sector by promoting the transition to electric, electric / hydrogen cars.

The Ukraine is going through an economic crisis caused by Russian aggression in 2014. The resulting massive attack on Ukraine’s energy sector is one of the most important elements of Russia’s hybrid war against its neighbour. More than half of the Ukraine's primary energy supply comes from local uranium and coal resources, although natural gas also plays an important role in its energy mix. Ukraine consumed about 1.5 trillion cubic feet of natural gas in 2014, with domestic production accounting for 47% of the total at about 700 billion cubic feet. The remainder of supply is made up by Russian natural gas, imported through the Bratstvo and Soyuz pipelines. Switching to renewables and increased energy efficiency are priorities especially important for Ukraine because it is one of the biggest energy consumers in the world [3]. The usage of fossil energy resources must be decreased – there are real concerns over the exhaustion of them and global climate changes due to consuming them. Other concern is that local energy markets indicates increased dependency on energy imports. These factors make the development of alternative energy sources and usage of renewable resources an

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urgent matter for Ukraine researchers and policy makers to strengthen independence [4].

Ukrainian and especially Latvian energy balance of solar energy share is growing slowly and one reason is necessity for energy accumulation. Energy storage capacity is an important value and must be planned for each solar/wind grid separately, depending on availability of local energy systems and actual geographic location. This article summarises experience of Ukrainian and Latvian researchers in scaling hydrogen energy technologies to facilitate energy storage in power systems operating from renewable resources. A planned theme in joint future collaboration project is dealing with the possibility of using solar energy in two countries - Latvia and Ukraine on the basis of particular application of distributed energy micro-grids in urban environment – attractive and functional lighting poles connected in micro-grids with a common energy storage option. Planned experiments and the expected benefits are addressed in this publication.

ENERGY STORAGE METHODS

A proper energy (electricity) storage can enhance the value of wind energy acquisition by dispatching that energy when it is needed rather than when it was originally generated. Multiple solutions are available and both fundamental as well as applied research in this field is still ongoing. The landscape of energy storage is extensive. The review of Sabihuddin et al., 2015 [5] has discussed 27 types of storage technologies. Some storage technologies are strongly coupled to particular generation technologies. Storage technologies have been compared numerically and qualitatively on the basis of such parameters as specific energy, energy density, lifespan, cycle life, self-discharge rate, capital costs of energy and power etc. (see Luo et al., 2015 [6]). For instance, pumped hydro storage (PHS) systems show strong similarities with hydro-electric plants and are often used in conjunction with nuclear facilities. Compressed air electricity storage systems (CAES) are much like peaking gas turbine plants. Thermal storage systems are integral parts of thermal (and solar thermal) plants and are often used in the context of steam generation and waste heat recovery for subsequent power plant cycles. Flywheel systems (FWS), in comparison to CAES, are fairly mature and commercially tested [5, 6]. They exhibit many advantages over both PHS and CAES solutions.

Most chemical energy storage systems have a number of common features, for instance: the electrodes, the electrolyte and the separators or membranes. Improvements have largely focused on materials [5]. A shift has occurred towards more reactive electrodes. These more reactive variants have shown the promise of increasing energy and power densities - the use of lithium (e.g., Li-Ion batteries) and oxygen/air based chemistries (i.e., metal-air batteries) reflects this trend. Nevertheless, virtually every chemical battery type has seen the utilization in different electricity storage systems.

Energy can be stored also using hydrogen as energy carrier, transforming electricity from renewables to hydrogen through electrolysis of water and storing this hydrogen in high pressure vessels, liquid form or as hydrides of specific materials [7]. Fuel cell (FC) is indispensable part in hydrogen storage system, as it increases in scale, operates much like traditional thermal generation plants, albeit converting fuel (hydrogen) directly to electricity. Fuel cells offer an alternative to burning, have high energy and power performance and have seen some commercial applications to large scale grid level storage/generation (Fig.1).

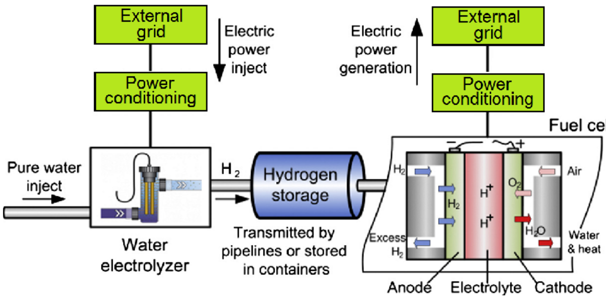

Fig.1. Topology of hydrogen storage system (electrolyser, storage vessel and fuel cell - after Luo et al, 2015)

However, there is a need, to reduce costs of hydrogen energy storage *systems even further in order to be com*petitive with other energy storage solutions. Traditional chemical batteries are likely to be strong contenders for small/middle scale storage at this point, though with additional research metal-air chemistries may hold future promise [6, 7]. FC and FWS are tested in large and small scale applications; therefore, these systems may be more relevant to deployment for distributed grid infrastructure [6]. For long-term storage (months, years) the hydrogen energy storage is competing not so much with overall efficiency (below 60%) but costs, ease of installation and multipurpose usage (electricity, heat and fuel for transport), see [5-7].

Despite the search for new ways to produce environmental friendly fuels, the focus of research is still concentrated on the possibility of producing hydrogen from water [7, 8]. Technology of hydrogen production based on the processes of decomposition of water by electrolysis, are widely used in various fields of modern industry. Compared with other methods of producing hydrogen, electrolysis systems are easily scalable and usable in various power applications. Therefore, urgent problem is the development of electrochemical technologies to generate hydrogen from water with minimal cost of electricity, especially in light of the expansion of the use this hydrogen as resource for environment-friendly energy in advanced technologies.

EXPERIMENTAL DETAILS

Micro-grid of 5 solar lighting poles (PV 200W and LED 100W each – see Fig.2) as prototype of renewable energy power plant and consumer simultaneously, self-made 2 different electrolysers (high pressure and pulse powered) connected with hydrogen storage in compressed gas cylinder and metal hydride tank accordingly is used as potential long-period energy storage facilities.

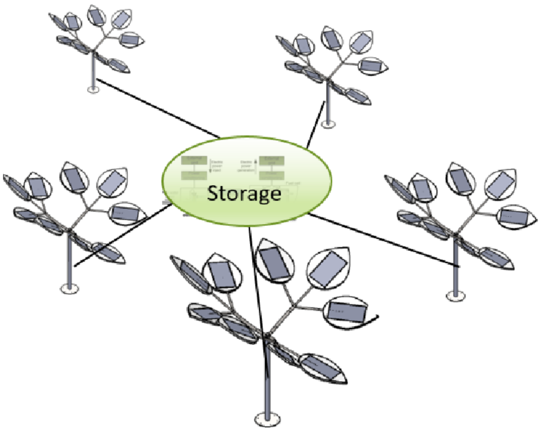

Fig.2. Principal scheme of micro-grid from 5 solar trees (light poles)

Energy excess transformation into hydrogen via water electrolysis

In industry, widely used conventional liquid alkaline electrolyte is chosen to ensure the generation of gases at pressure of 0.05 - 1.6 MPa in the temperature range from 333 K to 353 K and current density of 1200-2500 A/m^2 [8]. Thus the energy consumption (depending on the process temperature, pressure, quality of the electrode cell design, and other factors) varies in the range from 4.3 kWh/m^3 to 5.2 kWh/m^3 of hydrogen (H_2).

High pressure electrolysis

At AN Podgorny Institute of Mechanical Engineering Problems of NAS Ukraine has developed a technology of electrochemical production of hydrogen and oxygen at high pressure using a getter electrode and diaphragm-less cell design [9,10]. Operating temperatures are in the range of 280 K to 423 K, pressure range is from 0.1 to 70 MPa, electrolyte - 25% aqueous solution of alkali. Designed electrochemical method for the decomposition of water is a cyclic and consist of alternating in time processes of hydrogen and oxygen evolution. It means that comparing with traditional electrolysis were the reaction of water decomposition takes place continuously with simultaneous evolution of hydrogen and oxygen on electrodes in an electrochemical cell, in the proposed technology proceeds cyclic distribution of gases H_2 and O_2 to the consumer. In the first half-cycle, hydrogen is released at the passive electrode in a gaseous form and fed to the high pressure line, but oxygen is chemically bonded to the active electrode forming a chemical compound. In the subsequent half-cycle the hydrogen is carried out reduction of previously formed chemical compound on the active electrode, but oxygen is released at the passive electrode in gaseous form and fed to the high pressure line (Fig.3).

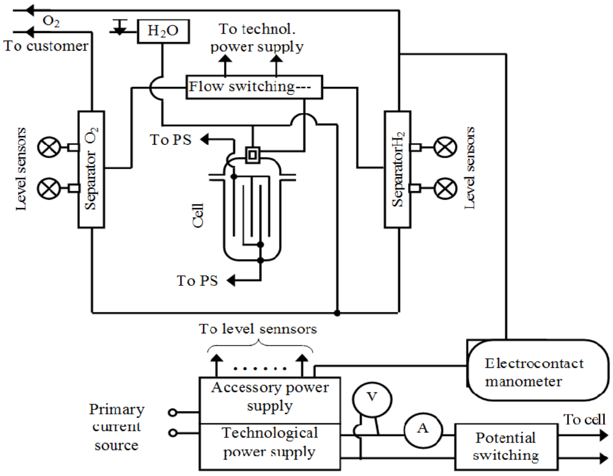

Fig.3. Schematic of an installation with an electrochemical cell using a gas-absorbing electrode

Pulse electrolysis

Typically direct current (DC) power is used in electrolysis; nevertheless, pulse DC voltage also can be used [11-13]. Bockris et al. [11] found that applying voltage pulses on an electrolysis cell, the long current tail is observed just after end of voltage pulse. Shimizu et al. [12] used inductive voltage pulses (200 ns) to power electrolysis cell and found that efficiency of electrolysis does not change by varying applied power. Researchers from Institute of Solid State Physics, University of Latvia [12] used inductive voltage pulses to compare different metals as cathode and found that concentration of dissolved hydrogen grows faster on metals with higher hydrogen evolution overvoltage and lower hydrogen solubility. In this work [12] we prove the fact that using inductive voltage pulses to power electrolysis cell, it is possible effectively reduce applied potential thanks to the possibility to separate both the charging current from the charge transition (Faradic) current in hydrogen evolution reaction.

Inductive voltage pulses were generated with an electric circuit (Fig.4) consisting from pulse generator, DC power source, field transistor and blocking diode.

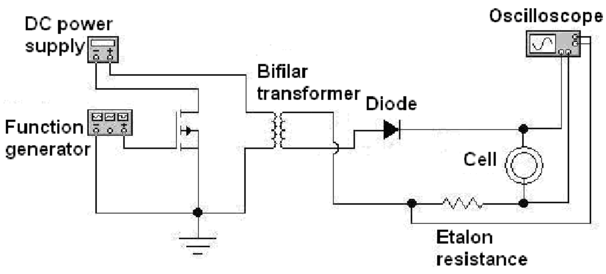

Fig.4. Experimental circuit for generation of inductive reverse voltage pulses

Special transformer is wound as bifilar from two wires twisted together. Obtained inductive reverse voltage pulses powers the primary winding in bifilar transformer and is directed through blocking diode. Resulting high voltage pulses with width $1{\cdot}10^{-6}$ s are obtained and used to power electrolysis cell. Two beam oscilloscope GWinstek GDS-2204 is used to register voltage and current (voltage drop on an etalon resistance) in circuit powering electrolysis cell.

Energy Storage

Battery, hydrogen and hybrid energy storage will be analysed for particular case - 5 small solar lighting poles (200W each) are connected in micro-grid with total installed power 1 kW (Fig.2). LED lights for each pole has maximum 100 W, electric system is designed to 12V and nominal current – 1 A. With smart power regulation (motion sensors in every pole) it is possible to reduce consumed power five times, accounting to micro-grid of 5 poles - from 0.1 to 0.5 kW. Volumes of energy necessary to be stored are calculated from actual amount of electricity to be consumed. In our case two consumption scenarios – one for particular day and second for average year should be combined. Daily amounts of harvested energy from the sun and the consumed in dark time is highly variable through year and for latitudes of Riga (Latvia): 56°57'0" N/24°6'0" E and Kharkiv (Ukraine): 49°55'0" N/36°19'0" E varies between 0.53 - 12.23 kWh/m^2 (Riga) and 1.67 – 12.12 kWh/m^2 (Kharkiv) [14].

The number of hours the sun is shining each day (that is the number of hours between sunrise and sunset) when averaged over the year are 12 hours multiplied by number of days in year everywhere in the world. It differs only in the maximum height of the sun above the horizon and an angle of the Earth's rotation axis with respect to the sun. Therefore in the Northern latitudes the average intensity is lower than at the Southern latitudes. Harvested energy from 5 poles is surplus from spring to autumn and deficit in winter time (Fig.5, calculated from [15]), that is 1/4th from year .

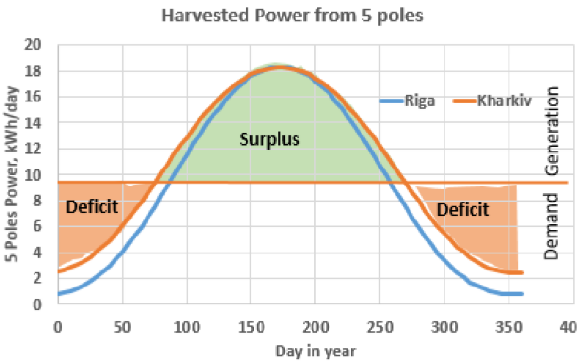

Fig.5. Annual solar generation versus demand for a solar system at latitudes of Riga (57N) and Kharkiv (50N)

Hydrogen is produced in water electrolysis using two different electrolysers. When high pressure electrolysis is used, typical gas vessels up to 200 bar can be connected directly to store hydrogen for winter time. The second option to produce hydrogen from water is low pressure electrolysis, and such hydrogen can be easily stored in metal hydride tank for utilization in winter time. Low temperature can decrease pressure of stored hydrogen in both cases (pressed and bind in crystal lattice). Therefore, the storage at least 1 meter below the ground, where constant temperature is maintained during the year, is desired.

Electricity generation

Proton electrolyte membrane fuel cell stack (PEMFC) 1 kW is used to generate electricity from stored hydrogen. As it could be understood from Fig.5, the need for additional electricity will arise of the dark and cold season only (November – February).

RESULTS AND DISCUSSION

High pressure electrolysis

The proposed technology of electrolysis for producing hydrogen and oxygen at high pressure eliminates the cost of electric energy transfer resistance separation membranes due to their absence [9,10]. This ensures the generation of H_2 (O_2) under high pressure, up to 200 bars without necessity for additional compressor. The advantage of the described method for obtaining hydrogen includes the ability to relatively simple (adjusting current) control of the reaction rate and thus the energy consumption, which is especially important when electricity from renewable energy sources of differing volatility (solar, wind) is used.

The process of hydrogen generation begins with applying negative potential to the passive electrode (Fig.6). The gas-absorbing active electrode operates as an anode at this stage. The water-dissociation reaction produces hydrogen and oxygen simultaneously. The hydrogen is isolated at the passive electrode in the gaseous state, and the oxygen is chemically combined at the active electrode (i.e., it is accumulated as an oxide). This operational sequence is provided by automatic switching of electrodes to act as anode/cathode electrodes.

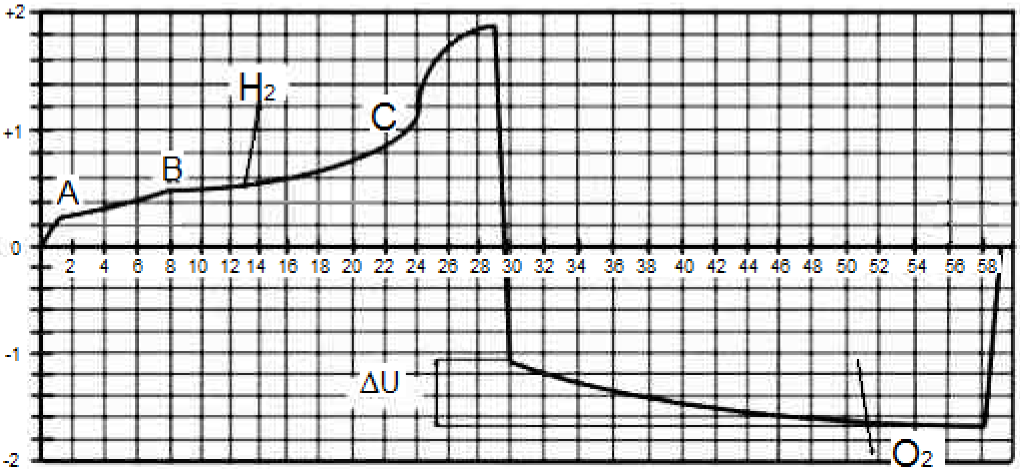

Fig.6. Change of voltage for hydrogen and oxygen isolation in the electrolysis process (Y-axis in Volts, X-axis in Minutes, from [9, 10]). Current density I = 200 A/m²; (A – B) – working area of the hemicycle; (B – C) – area of operation when there are the additional power inputs; ΔU – overvoltage under reduction of the active mass

Supplying the electrolysis cell with electric power is synchronized with an electromagnetic switch that controls the gas flow. As a result, hydrogen is isolated under high pressure and only fills a hydrogen pipeline. In the same manner, oxygen is fed to a separate pipeline. The water-dissociation reaction is initiated by increasing the voltage at the electrodes during the gas-generation process. Automatic control of the gas-generation process is based on the process's voltage-current characteristics, which were determined experimentally.

Pulse electrolysis is developed for efficient low-pressure electrolysis**.** The voltage to split water in practical electrolysis devices is higher than thermo-neutral cell voltage due transformation into heat, which heats up the cell. Therefore industrial electrolyser requires additional cooling and the value of DC voltage is defined [15]:

$$E = E_{rev} + loss, \tag{1}$$

where the loss is:

$$loss = E_{anode} + E_{cathode} + E_{mt} + IR, \tag{2}$$

where E_{anode} – activation overvoltage of the anode, $E_{cathode}$ – activation overvoltage of the cathode, E_{mt} – overvoltage of the mass transfer, IR – ohmic overvoltage (includes resistance in an electrolyte, on electrodes, leads). Current density is higher in industrial DC electrolysers, therefore applied voltage partly transforms into the heat, becoming typical loss in DC water electrolysis [16].

Inductive voltage and current pulse kinetics of water electrolysis cell (Fig.7) can be divided into two fundamentally distinct parts: a rapidly growing charging (1μs) and slowly descending discharge tail (about 20μs).

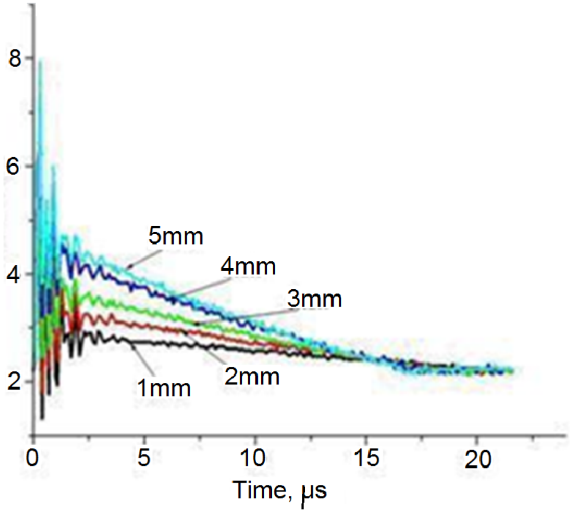

Fig.7. Voltage pulses registered with oscilloscope in 0.1 M KOH

The transition from the rapid charge to slow discharge tail happens through the breakpoint. By changing spacing between electrodes, the charging amplitude voltage pulse changes (Fig.7) – at 5mm distance the rapid charging ends at about 5V, while reducing the distance between the electrodes to 3mm and 1mm, the voltage value at the end of the charge drops to 4,2V and 3,8V respectively. To find the effective value of voltage taking into account the possible charge separation between cell's geometric capacitance and the electric double-layer charging with following Faraday reactions, the voltage oscillograms are modified to be compared with DC electrolysis. Comparison of volt-ampere curves shows that in the weak and also in 0.1 M KOH solution pulse electrolysis is more intense as the DC mode - slope is almost twice steeper. By contrast, in 0.3 and 0.5 M KOH solutions the steepness of pulse electrolysis volt-ampere curve is almost the same as the DC mode. This confirms previously discussed hypothesis that the inductive voltage pulse in rapid growing phase is charging only geometric capacity of electrolysis cell, and only then the charging of the electric double-layer capacity and parallel starting charge transfer (electrolysis) process. High power short pulse generator is elaborated to power 1 kW electrolysis unit with efficiency close to 67%.

Energy production, consumption and storage

In Latvia the sun shines average 1,790 hours per year, which is around half of the possible sunshine duration (clear weather). The sunniest days are from May to August, when the sun shines an average of 8-10 hours per day, but in contrast, from November to February the sun shines an average of only 2-3 hours a day [18]. From installed power of solar PV – 1 kW in micro-grid, it can be calculated maximal annual harvested energy in sunny hours – 1kW*1790h=1790 kWh, in case all modules are perpendicular to Sun. Let us assume that the rest 2590 day-light cloudy hours will 600 kWh more. In our case it means, that around 2400 kWh can be harvested from PV panels in an average year. The maximal consumed power for lighting in average year is calculated from equation 0.5kW*1/2 year (4380 h) = 2190 kWh which can be reduced 3-5 times with smart power management system. Let us assume that the 1/4th from 2190 kWh or 538 kWh will be energy shortages in winter and our storage facility should be with same energy capacity that is 538 kWh. If we want to store this energy amount in batteries, then the battery packs from 6 Tesla electric vehicles (85 kWh each) would be necessary. The Tesla Motors (Company producing most powerful electric vehicles) has just announced [20], that it will sell a battery pack for home use that will cost approximately $3500 for 10 kWh of power.

Hydrogen has one of the highest energy density values per mass. Its energy density is between 120 and 142 MJ/kg or 33-39 kWh/kg [19]. Assuming that the fuel cell can recover electricity from hydrogen with 70% efficiency, we obtain that for storage of 538 kWh is necessary about 20 kg of hydrogen or 21 reservoirs each 50 l with pressure 200 bar, or 212 Nm^3 gas at normal conditions. To produce such amount of hydrogen in summer time, in average 605 sunny hours are necessary, if electrolyser with capacity around 350 l/h is used.

CONCLUSIONS

In this paper innovative methods of water electrolysis are described – high pressure hydrogen gas generation up to 200 bar, and short pulse electrolysis of hydrogen gas at low pressure up to 3 bar. Both hydrogen-generation systems allow the chemical reaction rate to be controlled by controlling the current intensity (high pressure electrolysis) or pulse sequence rate (pulse electrolysis). This is especially important when the primary energy source for the electrolysis device is Sun or Wind with unpredictable and variable power affected by seasons, night/day changes, and climatic factors. Both investigated electrolysis technologies have shown high promise for use in the small and medium-sized self-sufficient objects or their micro-grids in combination with high-pressure or metal hydride hydrogen storage facilities.

It is calculated in case of 1 kW solar PV/0.5 kW LED lights micro-grid, the storage facility with capacity of 538 kWh is necessary. This amount of electricity can be recovered from 21 kg or 212 Nm^3 hydrogen gas, and to produce such amount of gas with electrolysis system having capacity 350 l/h, the 605 sunny hours in summer time are necessary.

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