Electrolysers Powered with Solar Energy

Ivaylo Y. Nedelchev [1], Rosen N. Vasilev [1]

[1] Technical Univercity, 1 Studentska str, Varna, Bulgaria

***Abstract* – The vast fossil fuel consumption and decreasing oil reserves and natural resources, enforce much more need of finding decision for renewable energies and development of constructions for using the so called green resources. One solution of this problem is combination ofalready established solar based sources and brown gas cell construction. Brown gas cell production is based on electrolysis of pure water and as a result generating a real gas fuel. This production can find large utility in different usages.**

***Keywords* – Brown gas, electrolyser, photovoltaic, efficiency.**

1. Introduction

Electrolysers for decomposition of water are also called brown gas generators (BGG). Theirelectrolyte is potassium hydroxide solution of water and production is gas mixture of oxygen and hydrogen. This mixture of gases is often called brown gas. It's known that chemical reaction between these both gases is exothermic and their mixture is more explosive.

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + 242{,}5kJ \qquad (1)$$

This energy can be used for heating in different conditions. The result of this is pure water, without any carbon emissions and pollutions. Needed energy for electrolysis can also be natural, using solar energy. Thus the entire cycle of energy could not be harmful for the nature.

Solar energy can be delivered either directly from solar panels or from solar installation with inverter [1],[2]. In the first case the brown gas cells can operate in low DC voltages 12V, 24V or 48V. In the second, theinvertor delivers 220V AC voltage and rectifier is needed for electrolysis. The advantage in the first way is simplicity and safety operating voltages, but the installation is highly dependent from variation of the solar irradiation during the day. This variant doesn't give stability of fuel production and system can't work by lack of light. Second way is actually well known like off-grid system of the solar installation. It is more complicated and expensive, but gives stability and opportunity of operating during the dark hours of the day.

In this report is represented a solar photovoltaic installation for feeding BGG. It was studieda construction of such type of generator whose gas production can be used for heating. In addition report represented both cases of solar feeding - directly from photovoltaic panels andwithinverter. It was calculated the gain of the entire installation and efficiency of thissystem for heating.

2. Construction and feeding of the brown gas generator

One of the ways to construct the electrolysers is with serial placed metal plates. The examined construction consists of stainless steel (316L type) plates mounted on the furrowed plate in a plexiglass container. The electrolyser's construction, shown in Figure 1, has two electrodes (anode and cathode) which feed all of the cells made from serial plates. The whole number of the cells is 53, fixed with 54 plates.

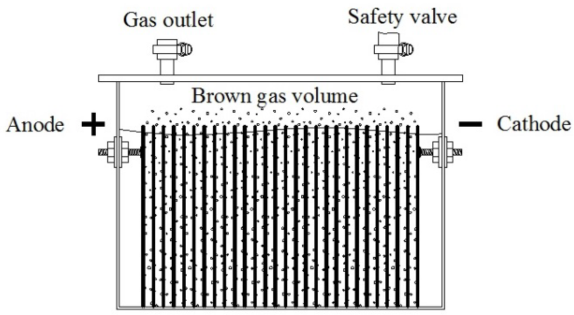

Figure 1. Brown gas generator with serial cells (316L type)

Applied voltage on the each formed cell depends on the value of the voltage between both electrodes and number of the plates. It can be calculated with:

$$U_C = \frac{U_S}{n-1}, \qquad (2)$$

where U_C is cell's voltage and U_S is source voltage on the main electrodes.

Theoretically, the minimum voltage on one cell must be at least 1,23V, in order to dissociate water's molecule. Then for this construction the needed voltage is 65,16V. Because of the losses in the electrolyte, actually optimum drop of the voltage upon each cell is found to be between 1,8V - 2,0V and the whole nominal voltage (U_N) then must be in the interval 95,5V to 106V.

The losses depend on volume of electrolyte between electrodes and respectively the main parameter for this construction is distance between them. On the one hand it must be small - for minimum losses in the electrolyte, but from other it mustn't be too small due to the adhesion on the electrodes of the produced gases. The smaller distances the harder will the releasing of produced gases be [3].

Electrical current of each cell was restricted to flow only in its own volume. This was reached by isolation of cell's edges from furrowed plate and decreasing level of the electrolyte to be set below from upper edge of the cell. In this way the current flows only between both separated plates i.e. consequentlythrougheach separatecell. Thuslosses depend on the distance between electrodes and they appear like heat in electrolyte. Due to highly explosive produced mixture of gases, electrolyser is protected with valve in case of explosion and entire system has two more elements of protection – water stop and flashback arresters.

Source of the energy for electrolyser can be either PV panels orinverter's solar installation.

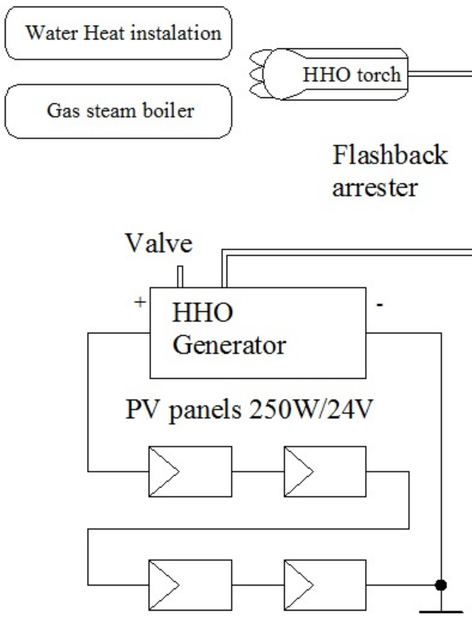

Figure2. Diagram of the brown gas generator sourced directly from photovoltaic panels

In Figure 2.is presented example type of heating installation and definite number of photovoltaic (PV) panels supplying energy directly to the brown gas generator. For this type of generator are needed four PV panels (if the nominal voltage is U_{PVN}=24V for each) in serial connection in order to achieve optimal voltage for gas production.

Typical I-V characteristic of the PV arraywith maximum power point (MPP) on itis shown in the Figure 3.

The curve of constant power is hyperbola (dashed line) that must have point of contact on I-V characteristic of PV. Different solar radiation causesshifting of the I-V curves and this leads to changing the maximum power point (MPP) on them.

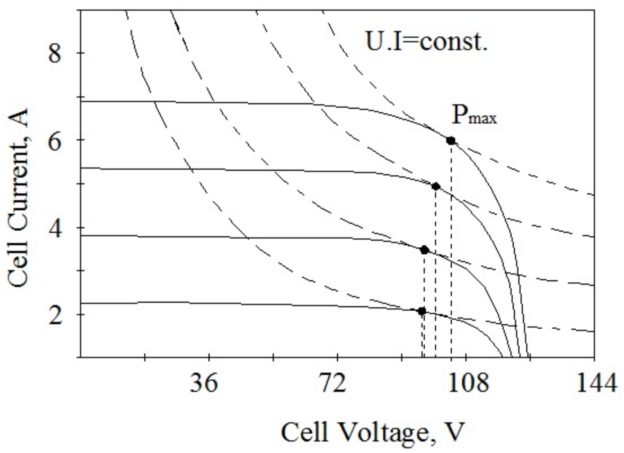

Figure 3. I-V characteristic of the PV panel array

For optimal work of the BGG U_N=95V-106V, MPP has to has project on the voltage axis within this voltage interval. Experiment shows that gas flow production (Q_G) is very sensitive to $U_N$changing. Only small change of the U_N (5-8%) causes big variation in Q_G (more than 60%).Thereforethe system is not too stable with respect to solar radiation and it's very important to obtain BGG I-V characteristic in order to achieve agreement with I-V characteristic of the PV array. Table 2.represents data of this I-V dependence of examined BGG with 53 cells and Figure 4 shows the trend of this curve.

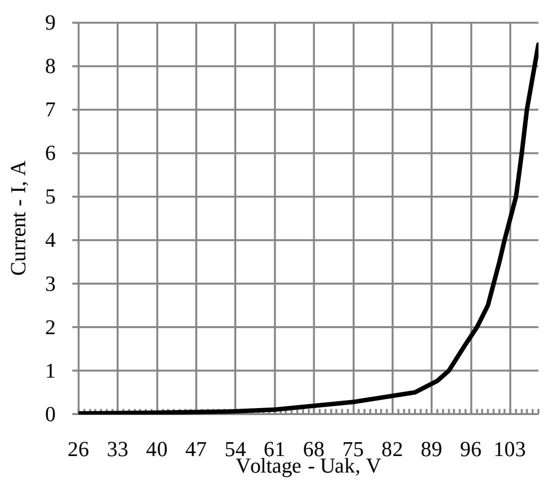

Figure 4.I-V characteristic of the BGG with 53 cells

Figure 5.shows curves of different types of loads (1, 2, and 3). For best coordination between BGG

and PV array curves, its point of cross-section must fall into MPP area. This area is defined as a part of I-V PV array curve in which solar panels give at least 90% energy from MPP.

Examined BGG and this type of PV array sequence have cross-section (p.A) into MPP area, what guarantees high system efficiency.

Table 2.Obtained data for I-V characteristic of theBGG with 53 cells

I(A)	0,75	1	1,5	2	2,5
Uak(V)	90,2	92,3	95,2	97,6	99,2
I(A)	3	3,5	4	4,5	5
Uak(V)	100,1	100,9	102,1	103,5	104,8
I(A)	6	7	7,5	8	8,5
Uak(V)	105,2	106,2	106,5	107	107,3

I-V characteristic of the BGG can be modified with adjustment concentration of the potassium hydroxidesolution. Thus point of cross-section can be optimized to fall within MPP area by definite levels of solar radiation. Different types of the BGGs require reorderingat the connectiondigram of the PV panels to achieve high level of coupling in the system.

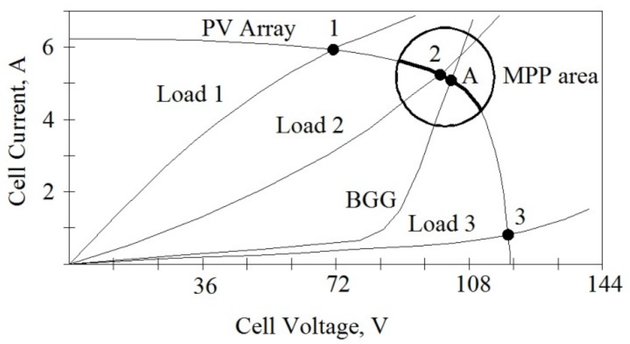

Figure 5.Cross-section between PV characteristic and different type of loads.MPP area.

Other way to deliver solar energy to BGG is using inverter which can supply AC voltage either from PV panels or from batteries.Its own parameters are given below in the table 2. The main are: operating AC and DC voltages, output power and current, efficiency [4].

Table 2. Inverter's parameters

Active output power [W]	2200
Input DC voltage [V]	24/48
Output AC voltage [V]	110V/220V
Output current [A]	11,5A
Efficiency [%]	95

The diagram of the entire solar installationsource - off-grid solar system, load – BGG is given in Figure6.For obtaining maximum active power over the BGG), its I-V characteristic (Figure4., table 1.) has to be in accordance with outer voltage of the inverter.

Because of the nominal voltage of BGG (U_N≈105V) and AC voltage of the inverter (U_i=220V), have tobe connected in serial two BGGs of this type at the output of the inverter. Power control unit (PCU) regulates source of the energy either from the PV panels or from the batteries. In this way, the system is more stable and independent from solar radiation.

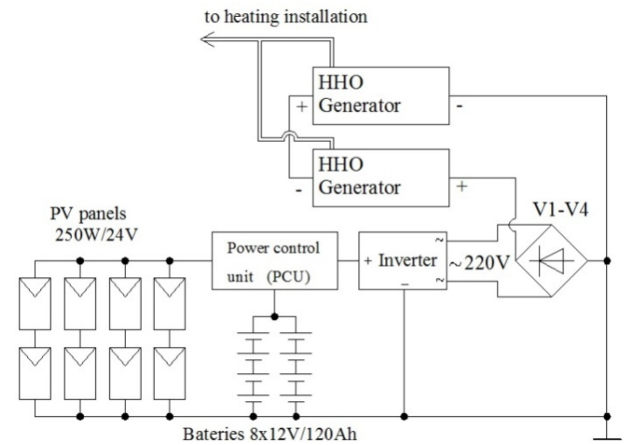

Figure6. Diagram of the brown gas generator sourced with solar system.

3. Input and apparent power. Power factorof the BGG

The main electrical parameters that need to be obtained are:working voltage (U_{ak}), current (I), input active power (P) and power factorof the BGG. Figure 7.shows electrical diagram of used measurement devices – ammeter, voltmeter and wattmeter, connected inV-A diagram on the load's side.Because of the pulsating character (after rectifier) of the measured values this type load has reactive behaviour. Thus in theexperiment are used TRMS (true r.m.s.) measurement devicesfor obtaining working r.m.s. current and r.m.s. voltage and wattmeter to measure dissipated active power over the BGG. Therefore,power factor of the BGG can be calculated with:

$$PF = \frac{P}{I.U_{ak}}, \quad (3)$$

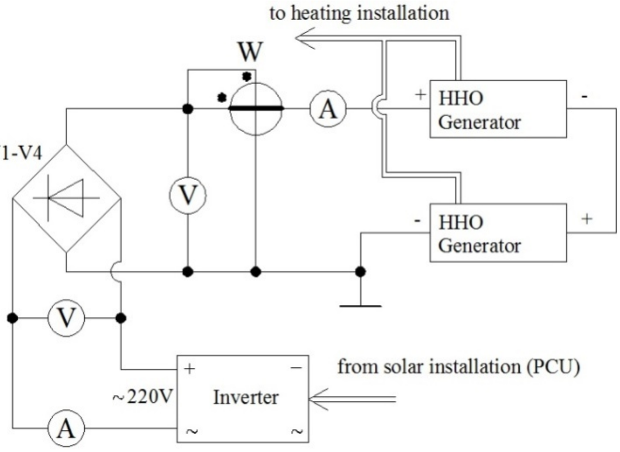

Figure 7.Measurement diagram in BGG electrical feeding with inverter

Due to the construction which consists of parallel metal plates and electrolyte between them, the loadis expected to has capacitivecharacter.

Table 3.Power factor of the BGG

Active input power [W]	340
Input pulse voltage [V]	105 (r.m.s.)
Input pulsecurrent [A]	4,5 (r.m.s.)
Power factor – PF [-]	0,72

During the experiment by different levels of working current in the interval 3A-6A, PF is changing between 0,65to 0,75.

4. Efficiency

For calculation efficiency of the system for heating it is needed to obtaindata for efficiency of its main modules – solar panels, inverter and brown gas generator.

$$\eta_{PV} = \frac{P_{DC}}{E.A_{PV}}, \tag{4}$$

where - η_{PV} is efficiency of the photovoltaic cell (for last models are reached 45%), P_{DC} [W] is its output power, A_{PV} [m^2] is total effective area and E [W/m^2] is sun radiation density. For inverter efficiency:

$$\eta_I = \frac{P_{out}}{P_{inv}}, \tag{5}$$

where P_{out} is output AC power of the inverter and P_{inv} is input DC power, commonly this value is between 88%-98%. Total efficiency of the solar system is formed with a few more system's conditions suchas: panel's dust, load's mismatches, wiring losses etc. This is shown in Figure8. For domestic heating wire losses do not exceed 0,5% and mismatch is minimized to 3-4%. Thus the whole losses of solar system conditions are no more than 5-6% for small domestic centrals. Thus can be assumed that $P_{DC} \approx P_{in}$.

Electrical efficiency of the BGG is:

$$\eta_E = \frac{E_Q}{E_{gen}} = \frac{t.q.Q_G}{t.P_{gen}} = \frac{q.Q_G}{P_{gen}}, \tag{6}$$

where E_Q, is the amount of energy in produced gas, E_{gen} is input electrical energy for definite time, q iscalorific value of the mixture - q =10104kJ/m^3.

E_Q depends on Q_G [m^3/min.] – gas flow during the time - t and q. E_{gen} is proportional to the input power P_{gen} and the same time t.

Regarding brown gas generator's efficiency and inverter's data, it must be mentioned that brown gas cell is working by power factor between 0,65-0,75, and invertor by 0,9-0,95.

Calculating efficiency of this system for heating usages more important are losses in outer DC cables, losses in mismatch and dust and power factor of the solar system and generator. Losses in all electrical components and electrolytes appear as heat and therefore can be calculated as a benefit.

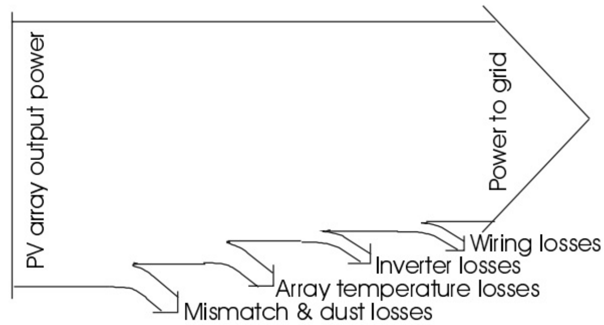

Figure 8. Losses in solar system

Taking into account thepower factors and total amount of losses in PV system – L1 (L1≈5%) and also the losses in rectifier – L2≈19%, the entire efficiency can be expressed with the equation:

$$\eta = \frac{P_{DC}.(1-L_1)}{E.A_{PV}}.\frac{P_{out}\,PF_{inv}.(1-L_2)}{P_{inv}}.\frac{q.Q_G.PF_{gen}}{P_{gen}} = \frac{(1-L_1).(1-L_2).q.Q_G.PF_{gen}.PF_{inv}}{E.A_{PV}} \tag{7}$$

In the upper expression it is assumed: $P_{DC} = P_{inv}$ and $P_{out} = P_{gen}$. Therefore the total efficiency of the system is expressed with coefficients of losses, power factors of modules and physical sizes. Practically for solar system without tracking devises, effective area can be reduced to 40% than physical surface of the panel (A_{PV}=0,6A_T). For 41°- 43° latitude,average sun radiation is E=1200W/m^2. It's known that the efficiency of solar system is not too high in regard to total radiation.

Crucialelement in the whole system is Faraday's efficiency η_F[%], of the electrolyser, which is expressed as a ratio:

$$\eta_F = \frac{\alpha.F.V_G}{I.t.V_M}, \quad (8)$$

where α is number of electrons being exchanged to produce one particle of gas at the electrodes, V_G is volume of produced gas mixture (V_G=t.$Q_G$at 20°C), I – current flowing in BGG during the reaction, t - taken time for the experiment, V_M – theoretical molar volume of gas production according to Faraday's laws of electrolysis (V_M=24.$10^{-3}$$m^3$/mol at 20°C), F=96484C/mol is Faraday's constant.

Table 4.Energy parameters.Electrical and Faraday's efficiency. Gas production

Input pulse voltage –U_{ak} [V]	105,7 (r.m.s.)
Input pulse current - I [A]	6,6 (r.m.s.)
Gas flow - Q_G [m^3/sec]x10^{-5}	5,83
Power factor – PF[-]	0,7
Active power – P [W]	490
Apparent power – S[VA]	697,6
Faraday's efficiency –η_F[%]	62,8
Electrical efficiency – η_E [%]	88,8

Experimental data for energy parameters and gas production aregiven in table 4. Calculations that concern Faraday'sand electrical efficiency don't take into account power factor of the cell, which has capacitive character.

5. Conclusion

Offered system which combines solar power and brown gas generator is a way to reducing carbon emissions. As a whole it has low efficiency with respect tototal radiated solar energy due to small efficiency of PV panels (45%) and rectifier (81%). Examined construction of brown gas generator gave middlelevel of Faraday's efficiency with approximately 62,8% and electrical efficiency 88,8% with respect to input active power. Energy characteristic of the system can be improvedby increasing efficiencyand power factor of the cell. This could be made either with electrical compensation of reactive component or with decreasing inherent capacity of the generator through changing the shape and the sizes of the construction.

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