Sustainability/Unsustainability Analyses of The Photovoltaic (PV) Electrolysis and Magnetic Heat Engine Coupled Novel System Used for Hydrogen and Electricity Generations

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Abstract

In this study, energy and exergy approaches, supported sustainability/unsustainability analyses, are applied to the photovoltaic (PV) electrolysis and magnetic heat engine, coupled novel system used for hydrogen and electricity generations. The results point out that the magnetic field does not only improve the hydrogen production, but also low-temperature heat can be harvested by magnetic heat engine, and relatively more efficient electricity can be generated, in comparison to other harvesters. Magnetic heat engine reaches its maximum power output at 7.6 T and the power output is 5.53 W. The considered novel system has greater energy and exergy efficiencies, which are around the 8%, at 7.6 T, besides, it is assumed sustainable at this value. Mostly the considered system is unsustainable, the main energy source is solar energy, and, since its unconsumable nature, loss of power can easily be compensated. In addition, it shows that most of energy input cannot be converted to electricity because of their ineffectiveness.

Keywords: Alkaline electrolyzer**;** Magnetic heat engine; Photovoltaic electrolysis; Sustainability

Nomenclature and formulae

C Concentration [mol/m^3]

D Diffusion coefficient [m^2/s]

$\dot{E}$ Energy rate [W]

F Faraday constant

G Solar irradiance [W/m^2]

I Cell current [A]

i Current density [A/cm^2]

i_{lim}^{o} Standard limiting current density [A/cm^2]

i_o Exchange current density (A/cm^2)

L Distance [cm].

LHV Lower heating value [J/kg]

$LMTD$ Logarithmic mean temperature difference [K]

$\dot{m}_{H_2}$ Hydrogen production flow rate [kg/s]

p_{H_2} Hydrogen partial pressure [bar]

p_{O_2} Oxygen partial pressure [bar]

P Power output [W]

P^{sat} Pressure [bar]

PV Solar Photovoltaic

P_{PV} Photovoltaic plant power output [W]

P_{cell} Power input to the electrolizer [W]

P_{mhe} Magnetic heat engine power output [W]

P_{net} System total power output [W]

$\dot{Q}$ Heat input rate [W]

Q_h Magnetic heat engine heat input rate [W]

Q_l Magnetic heat engine heat output rate [W]

R Universal constant of ideal gasses

R_{cell} Cell resistance [Ω]

t Magnetic heat engine times [s]

T Operating temperature of the electrolyzer [K]

T_0 Ambient temperature [K]

V_{act}^{an} Anode activation voltage [V]

V_{act}^{cat} Catode activation voltage [V]

V_{cell} Cell voltage [V]

V_{con} Concentration activation Voltage [V]

V_{ohm} Ohmic voltage [V]

V_{oc} Open circuit voltage [V]

V_{std}^{o} Standard voltage [V]

V_w Wind speed [m/s]

Greek letters

Ξ_{hyd} Hydrogen exergy ouput [W]

Ξ_d Exergy destruction [W]

Ξ_f Fuel exergy [W]

Ξ_{mhe} Magenetic engine exergy ouput [W]

Ξ_p Exergy production [W]

α_{an} Anode change transfer coefficient

α_{cat} Cathode change transfer coefficient

η_C Magnetic heat engine compression efficiency [%]

η_{PV} Photovoltaic plant efficiency [%]

η_e Magnetic heat engine expansion efficiency [%]

x Rate of magnetization

α Unavailability index

β Sustainability index

γ Exergetic ecological index

δ Exergetic inefficiency

ω PV plant mounting coefficien

Θ Fractional bubble coverage on the electrolyte surface

η First law effiency [%]

φ Exergy efficiency [%]

1. Introduction

Traditional energy resources such as petroleum, wood, coal, and natural gas have been utilized for many years, while they are consumed away, by using with population growth. These traditional resources are not sustainable, and not environmentaly friendly, due to their release of greenhouse gases into environment. So, investigation on alternative energy sources, with particular regards to renewable ones, has become a major issue in energy area. Renewable energies are clean and sustainable, and they are based on natural sources, like solar, tides, wind, geothermal, rain, etc. Solar energy represents a major renewable energy option, to be used for many applications, including off-network communities and remote areas, too (Caliskan *et al.*, 2013a). Sun is the primer energy source on Earth, with the result of generating winds and waver, and warm the surface (Caliskan *et al.*, 2013b).

Renewable energy sources can also be used to produse Hydrogen, which is an energy carrier. Hence solar is a promising source both to support the production of Hydrogenand and to turn hydrogen into an economical energy source. Hydrogen is sustainable, environmentally benign, versatil, energetically efficient, storable, transportable, and high density fuel (Caliskan *et al.*, 2013b).

There are several methods to produce Hydrogen, such as electrolysis, chemical reactions, thermolysis, etc. If the most ecological production method of Hydrogen should be used for the future, it is shown that electrochemical methods, based on electrity from renewable energy sources, are more usable. Afterward, the first days of researches on electrolysis methodology (Trasatti, 1999), many researchers have used this method to improve Hydrogen production capabilities. Electrolysis processes are the main production methods to produce Hydrogen, such as alkaline water (Dincer, 2012; Badwal *et al.*, 2013; Nikolic *et al.*, 2010), photovoltaic (Gibson and Kelly, 2008), and PEM (Carmo *et al.*, 2013; Grigoriev *et al.*, 2005).

Alkaline electrolysis technology has high efficiency and is the most advanced electrolysis method (Grigoriev *et al*., 2020; Parra *et al*., 2019). Alkaline electrolysis can be achived under high temperatures around 200 ^{o}C (Ebbesen et al, 2014). The efficiency of the alkaline water electrolysis process can be improved by the magnetic field (Koza *et al*., 2011; Koza *et al*., 2008). The magnitude of the magnetic field influences the formation of Hydrogen during the electrolysis of water. The most influential factor is the magnetic field gradient, that is applied to the water electrolysis process (Chibowski and Szczes, 2018; Lin *et al*., 2012). Malik *et al*. (2017) developed an effective magnetic catalyst for water electrolysis, and in their study, they found that an external magnetic field supports the maintainance of the catalyst activity. Iida *et al*. (2007) measured the cell voltage of an alkaline solution by using a magnetic field. A greater reduction in cell voltage has been shown in the magnetic field, and the amount of this decrease depends largely on the concentration of the electrolyte solution and the strength of the magnetic field. Lin and Hourng (2014) explored water electrolysis under magnetic field and pulse potential to generate efficiently hydrogen. In order to show that the magnetic field causes convection, Aaboubi *et al*. (1990) used the magnetic field, in place of rotating disk in electrode experiments, because of its property of convective mass transport. Various effects of different magnetic forces, affecting convection, were investigated by different researchers (Hinds *et al*., 2001; Bund *et al*., 2003; Weier and Landgraf, 2013; Baczyzmalski *et al*., 2015). Previous studies showed that the most effective magnetic force was the Lorentz force. Matsushima *et al*. (2013) introduced a contact angle and magnetic field equation function as a result of their investigation using glass electrodes. In another study on electrodes, Lin *et al*. (2012) studied different materials such as nickel, platinum, and graphite as electrode materials.

To assess thermodynamic systems, such as solar and electrolysis systems, both first and second laws of thermodynamics can be used. Exergy, also known as avialibility, is the quality of energy, and our approach is based on these two laws for investigation performance assessment, and design of systems. Indeed, sustainability assessment for thermal systems can be developed just by the exergy approach. Exergy is always evaluated with respect to a reference environment (environmental temperature), also named the dead state. Exergy allows us to analyse the thermodynamic behavior of the systems, in relation to the environment's condition. If the system is in thermal equilibrium with its environment, its exergy results null. So, it is important to assess the system according to exergy analysis (Caliskan *et al*., 2011). Differents author were studied exergetic performance of different sytems (Ekrataleshian et. al., 2021; Khanjari et. al., 2021; Jalili et. al., 2021; Alayi et al, 2021; Beigzadeh, 2021).

Low-temperature heat sources can be described as heat sources lower than 100^{o}C have a huge potential such as; industrial waste heat 6–8: 72% of the global primary energy consumption is released as waste heat; 63% of this heat is released at <100 ^{o}C, correspondingto a potential power production of 300 GW (Bermel et al, 2016; Cao et al, 2014; Johnson et al, 2008; Campana et al, 2013; Formn et al, 2016; Facchinetti et al, 2020, Meyer, 2016) Magnetic heat engines are the one way to utilize this low temperature heat source having a great potential.The considered system in this study is a solar energy-driven high-temperature alkaline electrolyzer and combined magnetic heat engine, which allows to utilize low temperature heat source to convert it to electricity. The current study has two main objectives:

(i) The first is to increase the Hydrogen production under a magnetic field, and to investigate the possibility of electricity generation by a magnetic heat engine, under an applied magnetic field;

(ii) The second objective is to perform sustainability/unsustainability analysis, in terms of thermodynamic approach.

According to the authors knowledge, this kind of hybrid system, under study in this paper, has first been investigated in the open literature. Additional electricity generation, via magnetic heat engine, is designed to store at the battery under no-existence of the solar energy, since the use aim is the continuous functioning. After having defined the performance parameters by a thermodynamic analysis and optimization of the power output, Hydrogen production, energy efficiency, exergy efficiency, the sustainability/unsustainability evaluations are obtained , and some suggestions anda results are presented and discussed. Consequently, the fundamental novelty of this study consists in:

(i) Solar photovoltaic (PV) electrolysis and magnetic heat engine systems is coupled in a new way for the hydrogen production and electric generation;

(ii) Not only energy, but also exergy and sustainability/unsustainability approach, are used to assess the new coupled hydrogen and electricity generation system, as first result in the scientific and technical literature.

2. System description

The considered system consists of a silicon PV panel, generating the electricity, required by the electrolyzer, an alkaline electrolyzer, a magnetic heat engine, and two permanent magnets. Here, the magnetic heat engine realizes the heat conversion into electricity, also by the temperature differentials to change the strength of magnetic fields. This change in the magnetic field produces electricity and supports the production of Hydrogen in the electrolyzer. The schematic layout of the photovoltaic (PV) electrolysis and magnetic heat engine coupled new system used for Hydrogen and electric generations

The main purpose of the considered system is Hydrogen production via solar energy and the application of a magnetic field increases hydrogen production in the solar electrolysis process. In addition to Hydrogen production, possible electric power generation, by means of magnetic heat engine, is studied, since this power can be utilized recently or stored for keeping Hydrogen production at night time. The operating principle of this hybrid novel system can be explained as follows; PV panel provides electrical power to electrolyzer and electrolyzer within magnetic field produce hydrogen. However, magnetic field harms PV cells in terms of electricity generation, panels should be deployed where they are not subjected to magnetic field. Moreover, Hydrogen is produced because of magnetic field and applied magnetic field can be used to generate electricity, which can be consumed or stored for hydrogen production at night time. Electric generation by magnetic heat engine requires heat, and heating and cooling processes change ferromagnetic materials magnetization, usable for generating power. Needed heat is met by waste heat removed by the electrolyzer. Brayton cycle is applied to magnetic heat engine as a power cycle.

In this reseach, we introduce the following assumption:

- Solar irradiance is assumed constant and equal to 800 W/m^2 (Skoplaki *et al*. ,2008);
- Ambient temperature is taken as 25^{o}C and wind speed is assumed as 1 m/s for simplication (Skoplaki *et al*. ,2008);;
- Cell area of the PV is taken as 1 m^2 to ease of calculations;
- Working temperature of the Alkaline electrolyzer is equal to 200 ^{o}C.

3. Analysis

In this section the analysis carried out is presented and analyzed for different subsystems.

3.1. Silicon PV cell

PV power output is the function of the ambient temperature, solar irradiance and wind speed.A simple correlation of the efficiency was presented by Skoplaki *et al*. in equation (1):

$$\eta_{PV} = 0.12\left[1 - 0.004\left(T_0 + \omega\frac{0.32G}{8.91+2V_w} - 25\right)\right] \quad (1)$$

Using eq. (1), one can get PV power [W]:

$$P_{PV} = 0.12G\left[1 - 0.004\left(T_0 + \omega\frac{0.32G}{8.91+2V_w} - 25\right)\right] \quad (2)$$

where G is the solar irradiance [W/m^2], T_0 is the ambient temperature [K], V_w is wind speed [m/s] and ω is mounting coefficient. Detailed investigation of the PV cell behaviours can be found in (Khatib et. al, 2021).

3.2. Alkaline Electrolysis

Analysis of the alkaline electrolyzer is performed by method defined by Abidin et.al . In here, produced hydrogen is needed and voltage and current must be calculated for this. Equataions for calculating them can be seen in eqs. (3)-(12)

The partial pressure of the hydrogen [bar]:

$$p_{H_2} = \left(\frac{1}{\frac{\varepsilon_{cat}}{\tau_{cat}} e^{\left(\frac{RTL_{cat-c}i}{2FP_{cat}D_{eff}^{cat}}\right)}} - 1 \right) P_{H_2O,KOH}^{sat} \tag{3}$$

The partial pressure of the oxygen [bar]:

$$p_{O_2} = \left(\frac{1}{\frac{\varepsilon_{an}}{\tau_{an}} e^{\left(\frac{RTL_{an-c}i}{2FP_{an}D_{eff}^{an}}\right)}} - 1 \right) P_{H_2O,KOH}^{sat} \tag{4}$$

where, R is the universal constant of ideal gasses, T is operating temperature [K] of the electrolyzer, F is Faraday constant, P is pressure [bar], D is the diffusion coefficient [m^2/s], i is the current density [A/cm^2] and L is distance [cm].

Open circuit voltage V_{oc} [V]:

$$V_{oc} = V_{std}^{o}(T - T_0)\frac{\Delta S^o}{nF} + \frac{RT}{2F}\left(ln\left(\frac{p_{H_2}\sqrt{p_{O_2}}}{a_{H_2O,KOH}}\right)\right) \tag{5}$$

where V_{std}^{o} is the standard voltage [V].

Activation voltages for anode and cathode are calculated [V]:

$$V_{act}^{an} = \frac{RT}{\alpha_{an}F} ln\left(\frac{i}{i_o^{an}(1-\Theta_{an})}\right) \tag{6}$$

$$V_{act}^{cat} = \frac{RT}{\alpha_{cat}F} ln\left(\frac{i}{i_o^{cat}(1-\Theta_{cat})}\right) \tag{7}$$

where α_{an} and α_{cat} are the change transfer coefficient for anode and cathode and $i_o$is the exchange current density (A/cm^2).

Fractional bubble coverage on the electrolyte surface can be found as follows:

$$\Theta = \left(-97.25 + 182\frac{T}{T_0} - 84\left(\frac{T}{T_0}\right)^2\right)\left(\frac{i}{i_{lim}}\right)^{0.3}\frac{P}{P - P^{sat}_{H_2O,KOH}}, \quad i \quad {}^{om}_{lim}{}_{lim} \qquad (8)$$

where i^{o}_{lim} standard limiting current density [A/cm^2].

Concentration activation Voltage [V]:

$$V_{con} = \frac{RT}{4F} ln \frac{C^{an}_{O_2,el}}{C^{an}_{O_2,o}} + \frac{RT}{2F} ln \frac{C^{cat}_{H_2,el}}{C^{cat}_{H_2,o}} \qquad (9)$$

where C is the concentration [mol/m^3].

Ohmic voltage [V] is calculated as follows:

$$V_{ohm} = IR_{cell} \qquad (10)$$

where I and R_{cell} are current [A] and cell resistance [Ω]. Finally, cell voltage V_{cell} [V] is:

$$V_{cell} = V_{oc} + V_{act} + V_{con} + V_{ohm} \qquad (11)$$

Power input to the electrolyzer P_{cell} [W] is calculated as follows:

$$P_{cell} = V_{cell}I \qquad (12)$$

3.3. Magnetic heat engine

Magnetic heat engine is a kind of heat engine which converts heat into electricty, since heat rates must be determined firstly. Heat input and output are written as follows:

$$Q_h = cB_1^2\left(\frac{1}{T_2} - \frac{1}{T_3}\right) = k_1 LMTD_h t_1 \qquad (13)$$

$$Q_l = c\left(\frac{B}{x}\right)^2\left(\frac{1}{T_1} - \frac{1}{T_4}\right) = k_2 LMTD_l t_2 \qquad (14)$$

where, t_1 and t_2 are the cycle times.

$$t_1 = \frac{cB_1^2\left(\frac{1}{T_2} - \frac{1}{T_3}\right)}{k_1 LMTD_h} \qquad (15)$$

$$t_2 = \frac{c\left(\frac{B}{x}\right)^2\left(\frac{1}{T_1} - \frac{1}{T_4}\right)}{k_2 LMTD_l} \qquad (16)$$

LMTD is a logarithmic mean temperature difference as expressed follows:

$$LMTD_h = ln\frac{(T - T_2) - (T - T_3)}{\left(\frac{T - T_2}{T - T_3}\right)} \qquad (17)$$

$$LMTD_l = ln\frac{(T_4-T_l)-(T_1-T_l)}{\left(\frac{T_4-T_l}{T_1-T_l}\right)} \quad (18)$$

Rate of magnetization (x) is expressed by;

$$x = \frac{B_1}{B_2} \quad (19)$$

Inefficiency rates can be described as degree of irreversibilities at the adiabatic processes. These parameters are called compression and expansion efficiencies to obtain similarity with the Brayton cycle which can be written as follows, respectively:

$$\eta_C = \frac{T_{2s}-T_1}{T_2-T_1}, \quad \eta_e = \frac{T_3-T_4}{T_{3s}-T_4} \quad (20)$$

The power output of the magnetic heat engine [W] is written using firt law of the thermodynamics and it expressed as follows:

$$P_{mhe} = \frac{Q_h-Q_l}{t_1+t_2} \quad (21)$$

3.4. Calculation methodology of the system

For the hybrid system, calculation methodology is expressed in this section. Total output power is calculated hydrogen power and output power of the magnetic heat engine. All power obtained by the PV is sent to electrolyzer to produce hydrogen. Hydrogen power is calculated as multiplying hydrogen production and hydrogen lower heating value (LHV)**.** It is written in eq. (22):

$$P_{hyd} = \dot{m}_{H_2} LHV_{H_2} \quad (22)$$

where $\dot{m}_{H_2}$and $LHV_{H_2}$are the produced hydrogen and lower heating value of the hydrogen. Exergy output of the hydrogen is calculated in eq. (23):

$$\Xi_{hyd} = \phi_{H_2} \dot{m}_{H_2} LHV_{H_2} \quad (23)$$

here, $\phi_{H_2}$is the exergetic coefficient of the hydrogen and, therefore, total energy and exergy outputs are calculated in eq. (24) and eq. (25) respectively:

$$P_{net} = P_{hyd} + P_{mhe} \quad (24)$$

$$\Xi_{net} = \Xi_{hyd} + \Xi_{mhe} \tag{25}$$

3.5. Thermodynamic analysis and sustainability/unsustainability indicators

Thermodynamic parameters consist of energetic and exergetic parameters. Energetic parameters are based on the first law of thermodynamics and it is related to energy balance in a system/cycle. For a cycle of heat engine, in which heat is converted into work, it can be expressed as:

$$\delta\dot{Q} - \delta P = \Delta\dot{E} \tag{22}$$

here, $\dot{Q}$is the heat input rate, P is the power output and $\dot{E}$ is the energy rate. The first law efficiency is described as ratio of energy output to energy input:

$$\eta = \frac{P}{\dot{Q}} \tag{23}$$

Energetic parameters are indicators of how much energy is used and converted to another form. However, energy analysis cannot respond to the question on "which is the quality of energy used". Exergy analysis, which is based on the first and second laws of thermodynamics, is introduced just to evaluate the quality of the energy. Irreversibility is the cause of the inefficiency of a system, and exergy analysis is applied to determine just the irreversibility and the components to be optimized. Exergy balance is expressed as follows:

$$\Xi_d = \Xi_f - \Xi_p \tag{24}$$

where, *f* dedicates "fuel", *p* dedicates "product" and *d* represents "destruction". Fuel exergy is the exergy input of the system to obtain useful product, which is called as product exergy. Exergy cannot be conserved and some piece of the exergy is always destroyed because of irreversibilities. This irreversible piece is named exergy destruction and shows loss of work potential. The lower value at the exergy destruction indicates the more quality employing of the energy. Another term is the exergy efficiency representing how a system is close to the reversible one and expressed as shown in eq. (25):

$$\varphi = \frac{\Xi_p}{\Xi_f} \tag{25}$$

Classical sustainability index is expressed as the ratio of the fuel exergy to the exergy destruction and it is expressed in terms of exergy efficiency as follows (Dewulf, 2000):

$$\beta = \frac{1}{1+\varphi} = \frac{\Xi_F}{\Xi_D} \tag{26}$$

The sustainability index (β) is a measure of the depletion of the energy source, it is expressed ratio of exergy equilavent of energy source(fuel exergy) to loss work (exergy destruction). it is clear that emissions, released into the environment, reduce as high exergy efficiency,or less exergy destruction rate; however, it does not provide any certain result of the amount of the emissions and their change.

Lucia *et al*. (2018) suggested a parameter called as unavailability index (α) as a measure of unsustainability in a system described as ratio of the exergy destruction to the product exergy. It is basically reverse of the sustainability index described in eq [26]:

$$\alpha = \frac{1}{\beta} \tag{27}$$

Exergetic ecological index (γ) considers basic exergetic parameters, fuel exergy, product exergy and exergy destruction at the same time. It is obtained by removing unavailability index from the exergy efficiency and it provides an information on how fuel source is used. For instance, if this index has negative value, it means depleted exergy is bigger than the useful exergy or power output and lower values give us the measure how a higher unuseful/depleted exergy bigger than useful product.

$$\gamma = 2\varphi - \alpha \tag{28}$$

The final one is called exergetic inefficiency (δ) (Lucia *et al*., 2020, Grisolia *et al.*, 2020) and it is calculated as the ratio of exergy destruction per product exergy, in other words, it is a comparison between loss work/ depleted exergy and useful work/product. Exergetic inefficiency is calculated as follows:

$$\delta = \frac{1-\varphi}{\varphi} \tag{29}$$

4. Results and discussion

This paper aims to emphasize two aspects: a magnetic effect increases production of hydrogen production at the electrolyzing process, and the use of this magnetic field for electric generation. In other words, magnetic field applied to electrolysis process to increase the hydrogen production can be utilized to operate magnetic heat engine. Magnetic heat engine is chosen since it can be used to generate electricty from the low temperature heat source. In this study heat rate rejected by the alkaline electrolyzer is assumed as source of the low temperature heat source. This kind of hybrid system is investigated in terms of sustainability/unsustainability which is based on exergetic approach. As it is explained in section 3, exergy is a measure of sustainability at the design stage of any heat engine/energy conversion device. However, before sustainability results, main parameters, like power output energy-exergy inputs and efficiencies, must be introduced. In addition to that relations, x and I between B are depicted in fig.2. Results are illustrated in Figs. 2-11, where magnetic field changes from 7.4 to 8.8 operating conditions of the magnetic heat engine. Results show that the magnetic heat engine reaches its maximum power output at 7.6 T and it is 5.53 W at this point.

Firstly, basic parameters which are power and exergy outputs shown in fig. 3. Total power output and exergy output rates are calculat by using eqs. (22)-(25) and results include power and exergy outputs of produced hydrogen and generated electricty. Results show that both of them, power and exergy outputs, reach their maximum points. The difference between maximum and minimum values of them are about 5 W. This value is relatively low and ithas resulted from since it is a small-scale system. As it can be seen in fig. 4 and Refs. (Aaboubi et al., 1990), hydrogen production increases with magnetic field and the power output generated by the magnetic heat engine is 5.48 W.Because of the changing tren of the magnetic heat engine, the power output and the exergy output of the system obey the same trend.

Energy and exergy efficiencies of the system are depicted in fig. 5. They have naturally same tendency with the power/exergy output of the system. Since energy and exergy inputs stay constant resulted from constant solar irradiance assumption their maximum otput values are provided at the same point where the magnetic heat engine power/exergy output is the maximum. Also, the energy and exergy efficiencies have very low values which are caused by the low efficiency of the PV cells. A closer investigation of energy/exergy efficiencies of magnetic heat engine, which can be seen in fig.6, It can be seen that exergy efficiency is much more bigger than the energy efficiency. This indicates that quality of energy conversion is more effective than the conversion of energy sources to power.

Exergy destruction rates of the considered system, which are shown in fig. 7, reach a minimum point at magnetic fiel at 7.6 T. This means that their lost power/depleted exergy is the minimum, in other words, inefficiencies are minimum in this point.

Sustainability/unsustainability analyses results are shown in figs. 8-11 where α, β, γ, δ prensent exergy inefficiency, sustainability index, exergetic ecological index and unavailability index, respectively. Figs.8 and 9 show the results of the hybrid system while Figs.10 and 11 are about the magnetic heat engine.In fig.8, exergetic inefficiency rate ranges from 10 to 12, which means exergy or potential power of the considered system is depleted more than 10 times per product exergy. The sustainability index is an indicator of thermodynamic environmental measure of any energy conversion system. It is a rate of the exergy destruction to exergy source, in other words, it is called as source depletion. This index is desired to be high as much as possible, which are not high for the considered system.The higher value means the higher amount of exergy sources is converted into useful exergy product. For the hybrid system, higher exergy inefficiencies and sustainability index values are consistent with each other, one of them has the maximum rate and the other has the minimum rate. The reason of these, they are strictly conneted with exergy destruction rate. Results of the magnetic heat engine show that the sustainability index has a maximum point, while exergetic inefficiency has a minimum. Unavailability and exergetic ecological indexes are shown in fig. 11. Exergetic ecological index is taken mostly negative values for both hybrid system and magnetic heat engine. This indicates that exergy destruction rate is bigger than product exergy and these negative values are about -0.8 for the hybrid system, which represents about 80% of the fuel exergy is not utilized effectively and depleted. For effective usage of the energy source, this value should be positive and as higher as possible. Magnetic heat engine has some positive points at 7.5 T and 7.6 T; however, these are still low and this reveals that product exergy and exergy destruction rates are nearly equal. With a detailed analysis is seen that extremum points are obtained where magnetic heat engine power output is the maximum and the sustainability of the system is high at these points.

According to the results, the considered system may not be assumed as sustainable. However, this system is driven by solar energy which is limitless and has no harmful environmental effects. Therefore, thermodynamic sustainable indexes do not provide any certain information about resource depletion or possible environmental effects. Yet, it would be a great mistake to say that it cannot be applied to renewable energy systems. Since these indexes provide information about power loss and irreversibilities directly connected to the efficiency and they are very useful to diagnose what is wrong with the system and their improvement potential consisting of information of where they and how big they are. For fossil fuel-based or non-renewable systems, they are good indicators for evaluating sustainability in terms of thermodynamics point of view, although they are insufficient since they have indirect connection to the economy and environment. The sustainability concept should involve energy, economic, environmental and social aspects altogether and these kinds of thermodynamical sustainable indexes do not provide anyenvironmental, economic but they give a detailed information in terms of energy aspects. According to these results, more comprehensive indexes should be tried to develop and it is another possibility to develop different sustainability indexes for renewable and non-renewable resources in terms of energetic aspects.

5. Conclusion

In this study, energy and exergy approaches supported sustainability/unsustainability analyses are applied to the PV electrolysis and magnetic heat engine coupled novel system used for hydrogen and electricity generations. The main conclusions of this study can be summarized as follows:

- Magnetic field does not only improve the hydrogen production but also low-temperature heat can be harvested by magnetic heat engine and relatively more efficient electricity can be generated compared to other harvesters.

-Magnetic heat engine reaches its maximum power output at 7.6 T and it is 5.53 W at this point.

-The considered novel system has greater energy and exergy efficiencies, which are around the 8%, at 7.6 T, besides, it is assumed sustainable at this value.

- Exergetic inefficiency rate ranges from 10 to 12.

- Exergetic ecological index is taken mostly negative and these negative values are about -0.8

- Mostly the considered system is unsustainable, the main energy source is solar energy and since its unconsumable nature, loss of power can be compensated easily. In addition, it shows that most of energy input cannot be converted to electricity because of their ineffectiveness.

- Finally, the authors emphasize that more comprehensive sustainability indexes should be presented and some different indicators should be developed for renewable and non-renewable systems for energetic evaluation.

6. References

Aaboubi O, Chopart J, Douglade J, Olivier A, Gabrielli C, Tribollet B, “Magnetic field effects on mass transport” J Electrochem Soc, 137 (1990), pp. 1796-1804

Abdin Z, Webb C J, E. Gray M A., "Modelling and simulation of an alkaline electrolyser cell" Energy 138 (2017) 316-331

Alayi R, Kumar R, Seydnouri SR, Ahmadi MH, Issakhov A, Energy, environment and economic analyses of a parabolic trough concentrating photovoltaic/thermal system International Journal of Low-Carbon Technologies, 16, 2021, 570–576.

Baczyzmalski D, Weier T, Kähler CJ, Cierpka C, "Near-wall measurements of the bubble-and Lorentz-force-driven convection at gas-evolving electrodes" Exp Fluids, 56 (2015), p. 162

Badwal SPS, Giddey S, Munnings C., Hydrogen production via solid electrolytic routes. Wiley Interdiscip Rev Energy Environ (2013), 10.1002/wene.50

Beigzadeh M, Pourfayaz F, Ghazvini M, Ahmadi MH, Energy and exergy analyses of solid oxide fuel cell-gas turbine hybrid systems fed by different renewable biofuels: A comparative study, Journal of Cleaner Production, 280, 2021, 124383.

Bund A, Koehler S, Kuehnlein H, Plieth W, "Magnetic field effects in electrochemical reactions", Electrochimica Acta, 49 (2003), pp. 147-152

Caliskan H, Dincer I, Hepbasli A. Energy, exergy and sustainability analyses of hybrid renewable energy based hydrogen and electricity production and storage systems: Modeling and case study. Applied Thermal Engineering (2013a), vol. 61, pp. 784-798, 10.1016/j.applthermaleng.2012.04.026.

Caliskan H, Dincer I, Hepbasli A. Exergoeconomic and environmental impact analyses of a renewable energy based hydrogen production system. Int J Hydrogen Energy (2013b), pp. 6104-6111, http://dx.doi.org/10.1016/j.ijhydene.2013.01.069.

Caliskan H, Hepbasli A, Dincer I, Exergy analysis and sustainability assessment of a solar-ground based heat pump with thermal energy storage. Journal of Solar Energy Engineering (2011), vol. 133, paper no: 011005, pp. 1-8, https://doi.org/10.1115/1.4003040.

Campana F., Bianchi M., Branchini L., De Pascale A., Peretto A., Baresi M., Fermi A.,Rossetti, R.Vescovo N., ORC waste heat recovery in European energy intensiveindustries: energy and GHG savings. Energy, Convers. Manage. 76, 244–252.

Carmo M, Fritz DL, Mergel J, Stolten D., A comprehensive review on PEM water electrolysis. Int J Hydrogen Energy (2013), pp. 4901-4934, 10.1016/j.ijhydene.2013.01.151

Chibowski E, Szcześ A., Magnetic water treatment–A review of the latest approaches. Chemosphere (2018), pp. 54-67, 10.1016/j.chemosphere.2018.03.160

Dewulf, J., H. van Langenhove, J. Mulder, M. M. D.van den Berg, H. J. van der Kooi, and J. deSwaan Arons. Illustration towards quantify-ing the sustainability of technology.Green Chem-istry2(3), (2000), pp. 108–114

Dincer I., Green methods for hydrogen production. Int J Hydrogen Energy (2012), pp. 1954-1971, 10.1016/j.ijhydene.2011.03.173

Ebbesen S D, Jensen S H, Hauch A, Mogensen M B, “High Temperature Electrolysis in Alkaline Cells, Solid Proton Conducting Cells, and Solid Oxide Cells” Chem. Rev., 114 (2014) 10697−10734

Ekrataleshian A, Pourfayaz F, Ahmadi MH, Thermodynamic and thermoeconomic analyses and energetic and exergetic optimization of a turbojet engine, Journal of Thermal Analysis and Calorimetry 145, 2021, 909–923.

Facchinetti I, Ruffo R, La Mantia F and Brogioli F. Thermally Regenerable Redox Flow Battery for Exploiting Low-Temperature Heat Sources Cell Reports Physical Science 1, 100056 May 20, 2020.

Fahidy T Z, “Hydrodynamics models in electrolysis” Electrochemica Acta 18 (1973) 607-614

Forman C., Muritala I.K., Pardemann R., and Meyer, B. (2016). Estimating the global waste heat potential. Renew. Sustain. Energy Rev. 57. 1568–1579.

Gibson TL, Kelly NA., Optimization of solar powered hydrogen production using photovoltaic electrolysis devices. Int J Hydrogen Energy, 33 (21) (2008), pp. 5931-5940, 10.1016/j.ijhydene.2008.05.106

Grigoriev SA, Fateev VN, Bessarabov DG, Millet P, “Current status, research trends, and challenges in water electrolysis science and technology”, International Journal of Hydrogen Energy, s. S0360319920310715, Nis. 2020, doi: 10.1016/j.ijhydene.2020.03.109.

Grigoriev SA, Porembsky VI, Fateev VN., Pure hydrogen production by PEM electrolysis for hydrogen energy. Int J Hydrogen Energy (2006), pp. 171-175, 10.1016/j.ijhydene.2005.04.038

Grisolia, G., Fino, D., Lucia, U. Thermodynamic optimisation of the biofuel production based on mutualism. Energy Reports 6 (2020), 1561-1571

Hinds G, Coey J, Lyons M, “Influence of magnetic forces on electrochemical mass transport”, Electrochem Commun, 3 (2001), pp. 215-218

Iida T, Matsushima H, Fukunaka Y, “Water electrolysis under a magnetic field”, J Electrochem Soc, 154 (2007), pp. E112-E115

Jalili M, Ghasempour R, Ahmadi MH, Chitsaz A, Holagh SG, Exergetic, exergo-economic, and exergo-environmental analyses of a trigeneration system driven by biomass and natural gas, Journal of Thermal Analysis and Calorimetry (2021), article in press.

Khanjari A., lMahmoodi E., Ahmadi MH, Energy and exergy analyses of solid oxide fuel cell-gas turbine hybrid systems fed by different renewable biofuels: A comparative study,Renewable Energy.160, 2020,231-249.

Khatib, Tamer, and Wilfried Elmenreich. Modeling of photovoltaic systems using Matlab: Simplified green codes. John Wiley & Sons, 2016.

Koza JA, Mühlenhoff S, Zabiński P, Nikrityuk PA, Eckert K, Uhlemann M. Hydrogen evolution under the influence of a magnetic field. Electrochim Acta, 56 (6) (2011), pp. 2665-2675, 10.1016/j.electacta.2010.12.031

Koza JA, Uhlemann M, Gebert A, Schultz L., Desorption of hydrogen from the electrode surface under influence of an external magnetic field. Electrochem Commun, 10 (9) (2008), pp. 1330-1333, 10.1016/j.elecom.2008.07.003

Lin MY, Hourng LW, "Effects of magnetic field and pulse potential on hydrogen production via water electrolysis" Int J Energy Res, 38 (2014), pp. 106-116

Lin MY, Hourng LW, Kuo CW., The effect of magnetic force on hydrogen production efficiency in water electrolysis. Int J Hydrogen Energy, 37 (2) (2012), pp. 1311-1320, 10.1016/j.ijhydene.2011.10.024

Lucia, U., Grisolia, G. Cyanobacteria and Microalgae: Thermoeconomic considerations in biofuel production. Energies 11 (2018), 156

Lucia, U., Fino, D., Grisolia G. Thermoeconomic analysis of Earth system in relation to sustainability: a thermodynamic analysis of weather changes due to anthropic activities. Journal of Thermal Analysis and Calorimetry, (published on journal web page on 12 July 2020) in press, https://doi.org/10.1007/s10973-020-10006-4

Malik B, Anantharaj S, Karthick K, Pattanayak DK, Kundu S, "Magnetic CoPt nanoparticle-decorated ultrathin CoIJOH)2 nanosheets: an efficient bi-functional water splitting catalyst, Vol 7 (2017), pp. 2486-2497

Matsushima H, Iida T, Fukunaka Y, "Gas bubble evolution on transparent electrode during water electrolysis in a magnetic field" Electrochimica Acta, 100 (2013), pp. 261-264

Nikolic VM, Tasic GS, Maksic AD, Saponjic DP, Miulovic SM, Marceta Kaninski MP., Raising efficiency of hydrogen generation from alkaline water electrolysis - energy saving. Int J Hydrogen Energy, 35 (22) (2010), pp. 12369-12373, 10.1016/j.ijhydene.2010.08.069

Parra D, Valverde L, Pino FJ, Patel MK, “A review on the role, cost and value of hydrogen energy sys-tems for deep decarbonisation”, Renewable and Sustainable Energy Reviews, c. 101, ss. 279-294, Mar. 2019, doi: 10.1016/j.rser.2018.11.010.

Skoplaki E, Boudouvis A G, Palyvos J A, “A simple correlation for the operating temperature of photovoltaic modules arbitrary mounting” Solar Energy Materials & Solar Cells 92 (2008) 1393– 1402.

Trasatti S, “Water electrolysis: who first?”, Journal of Electroanalytical Chemistry, c. 476, sy 1, ss. 90-91, Eki. 1999, doi: 10.1016/S0022-0728(99)00364-2

Weier T, Landgraf S, “The two-phase flow at gas-evolving electrodes: bubble-driven and Lorentz-force-driven convection”, Eur Phys J Special Top, 220 (2013), pp. 313-322

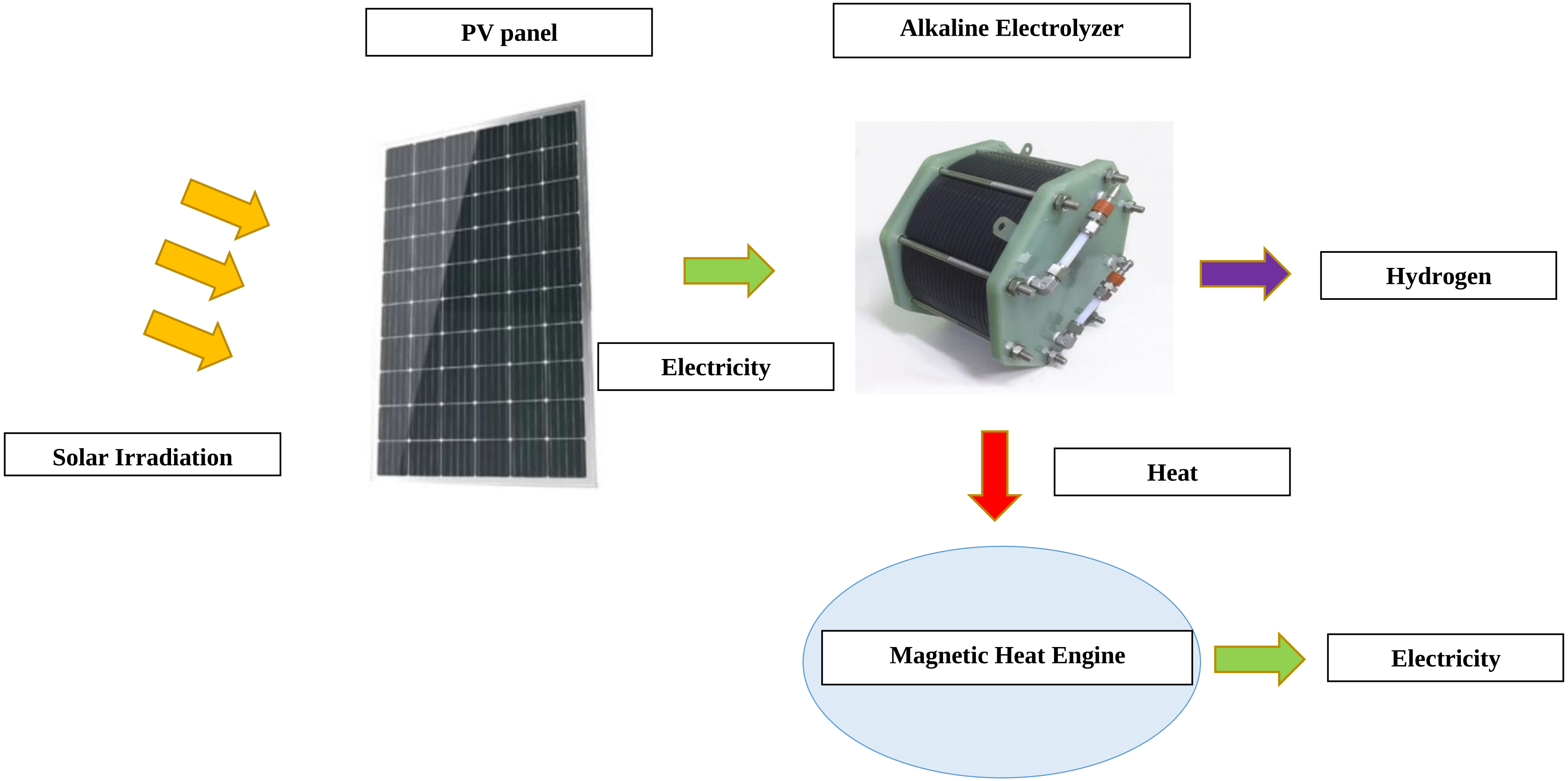

Fig. 1. Schematic of the system

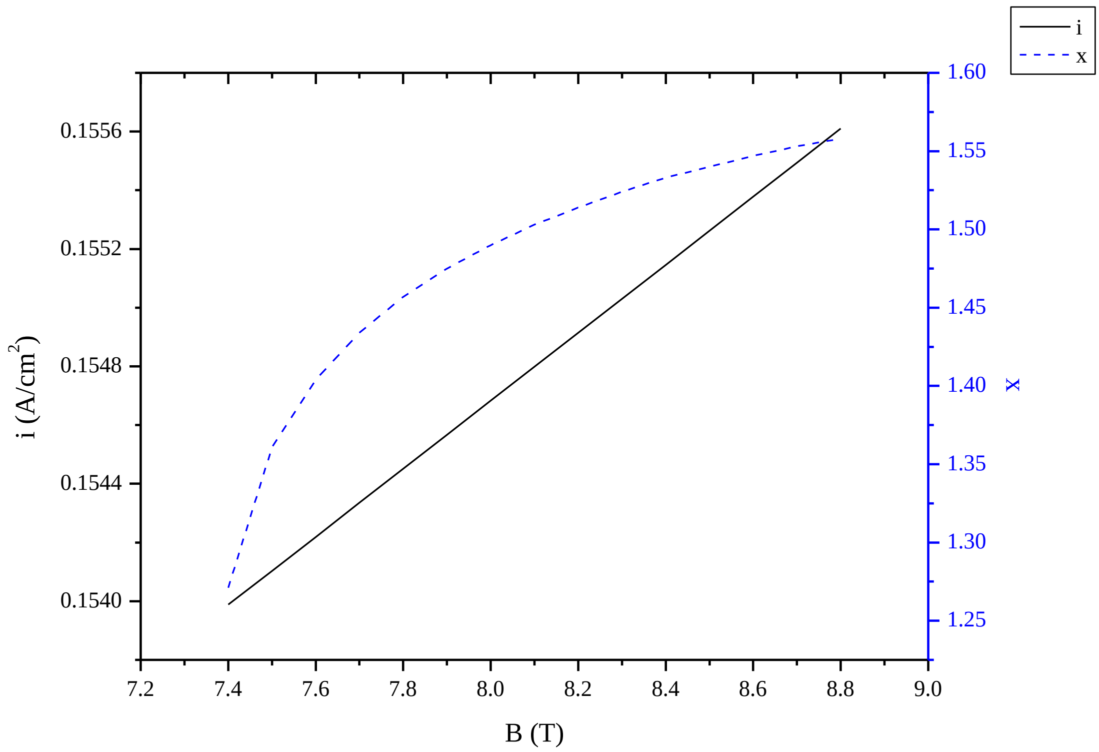

Fig.2. Connection current density and rate of magnetic fields.

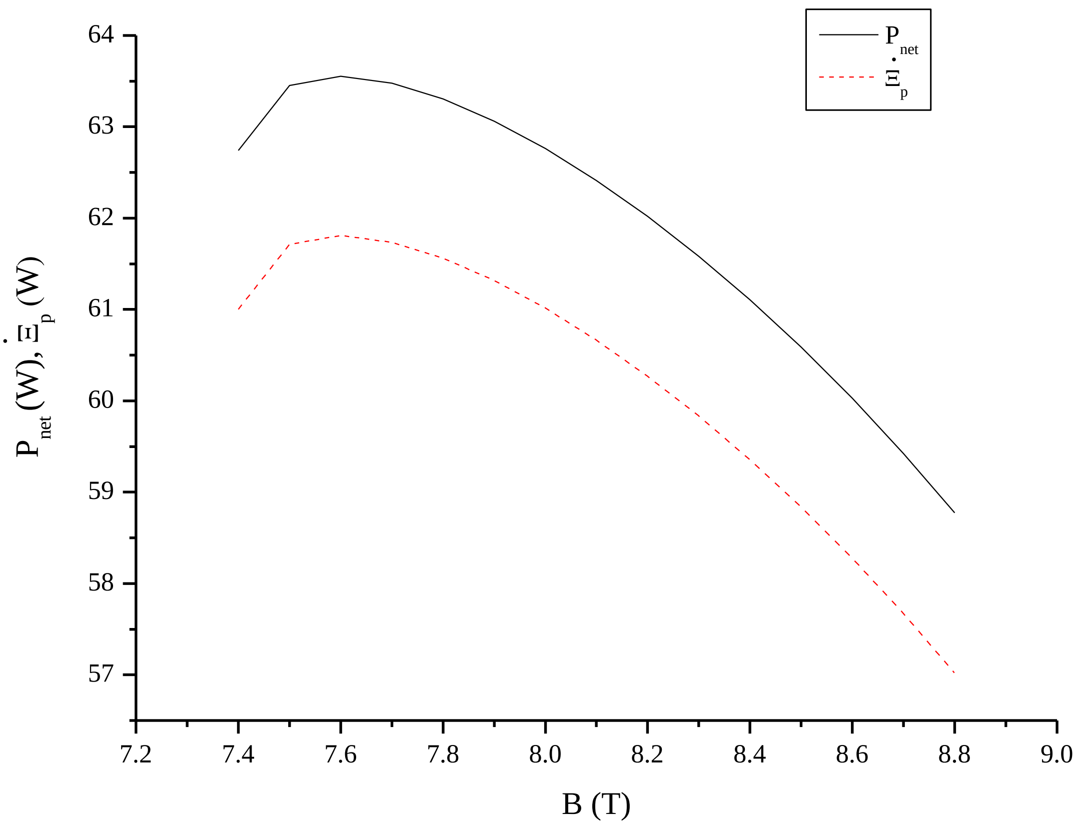

Fig.3. Variation of the power and exergy outputs with magnetic field.

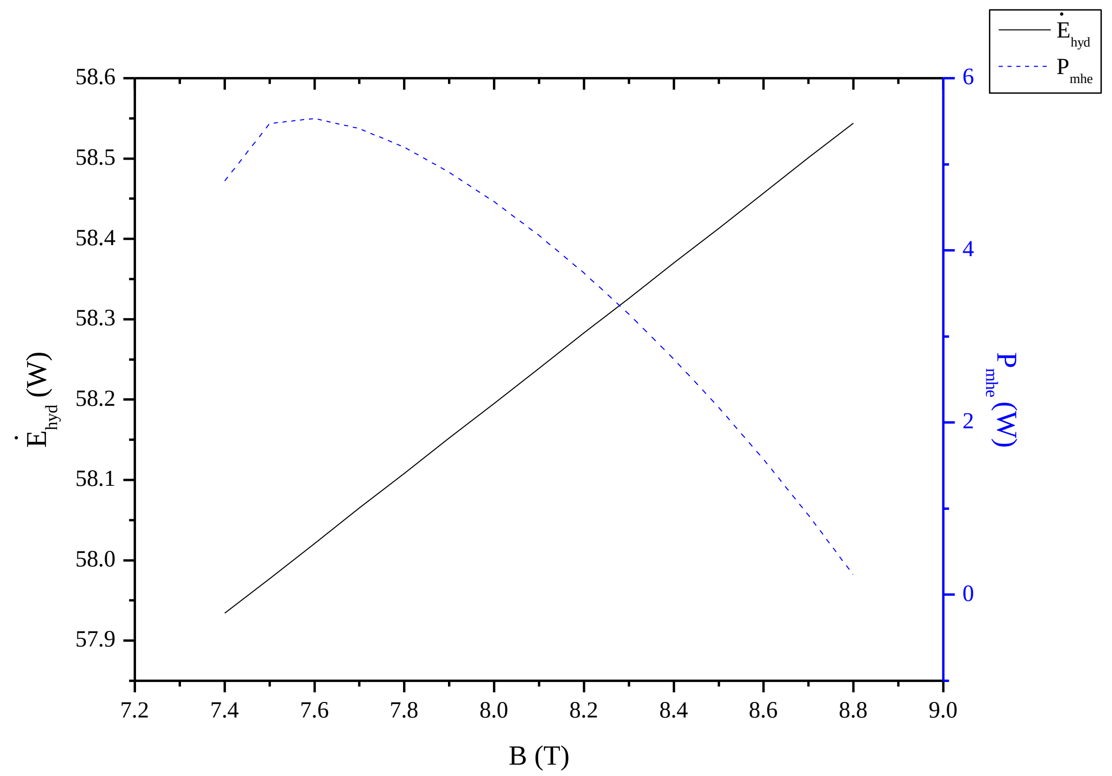

Fig.4. Variation of the power out of the magnetic heat engine and hydrogen energy output with magnetic field.

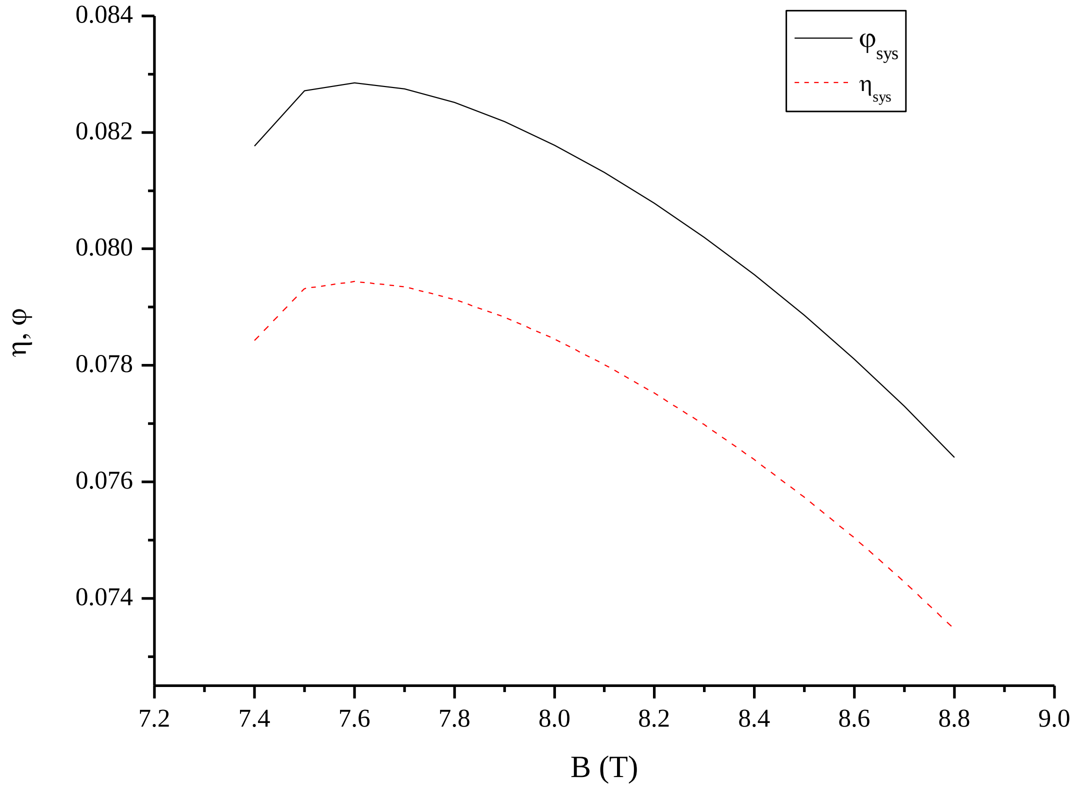

Fig.5. Variation of the energy and exergy efficiencies of the hybrid system with magnetic field.

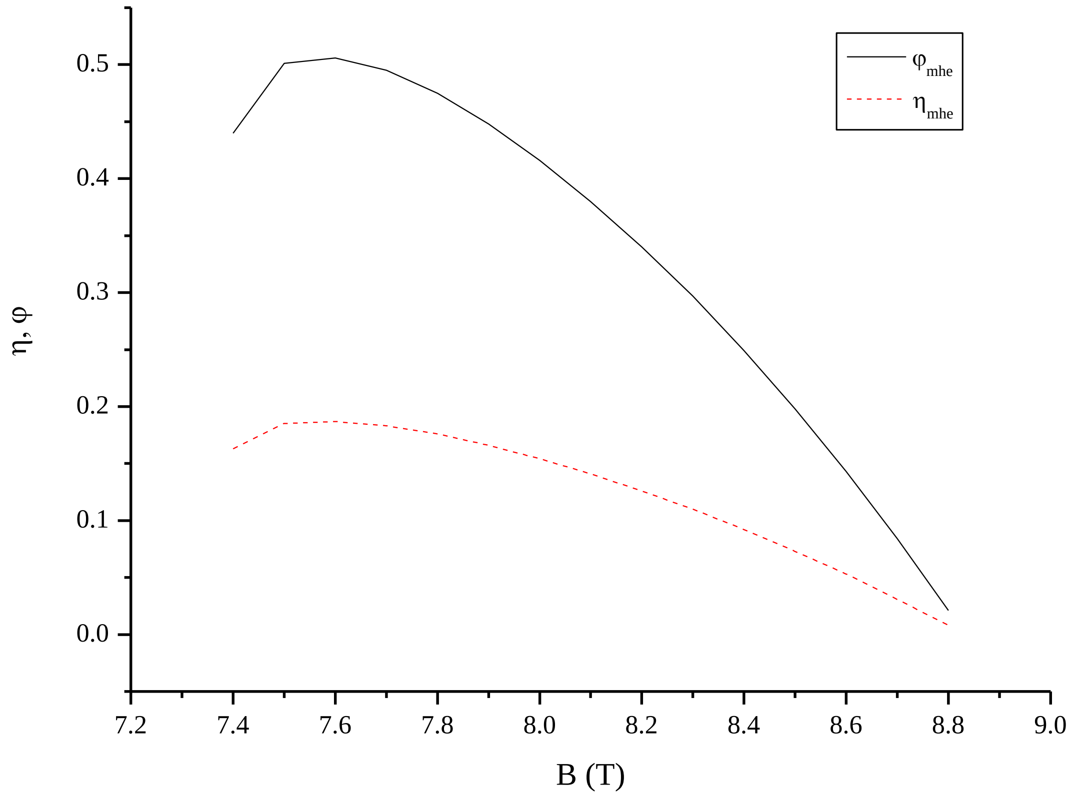

Fig.6. Variation of the energy and exergy efficiencies of the magnetic heat engine with magnetic field.

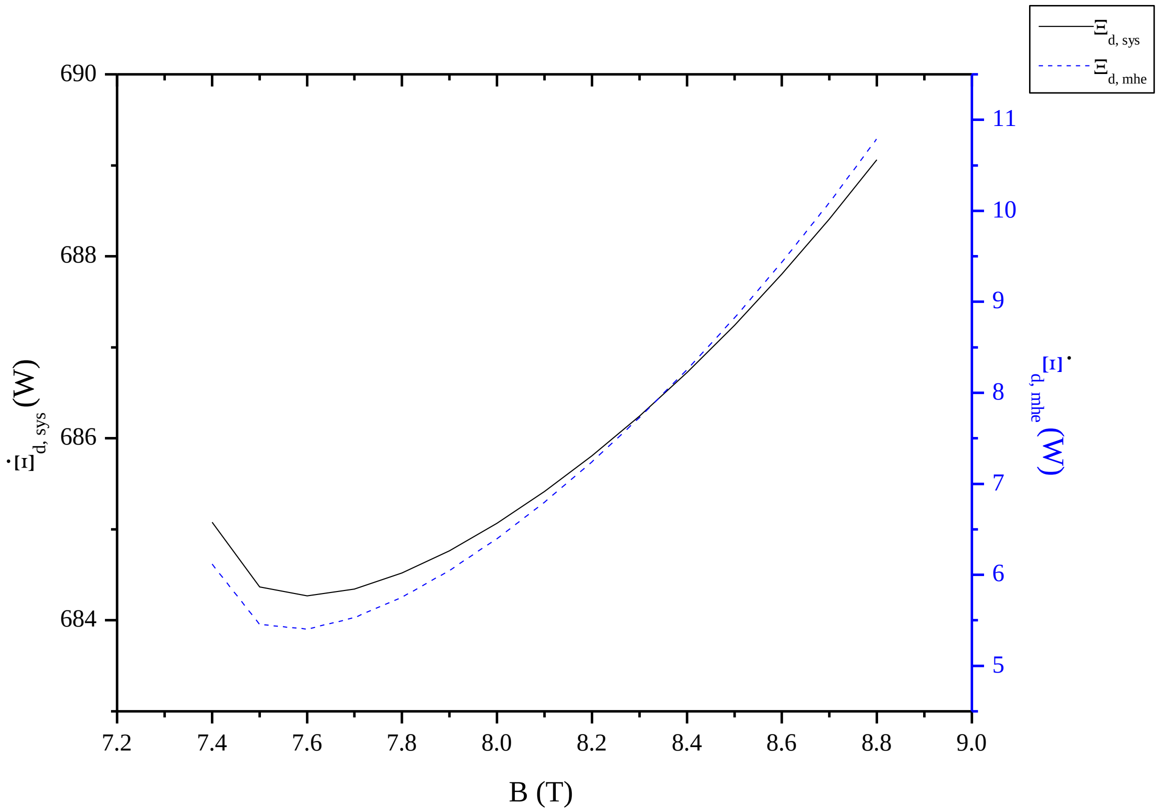

Fig.7. Variation of the exergy destruction rates with magnetic field.

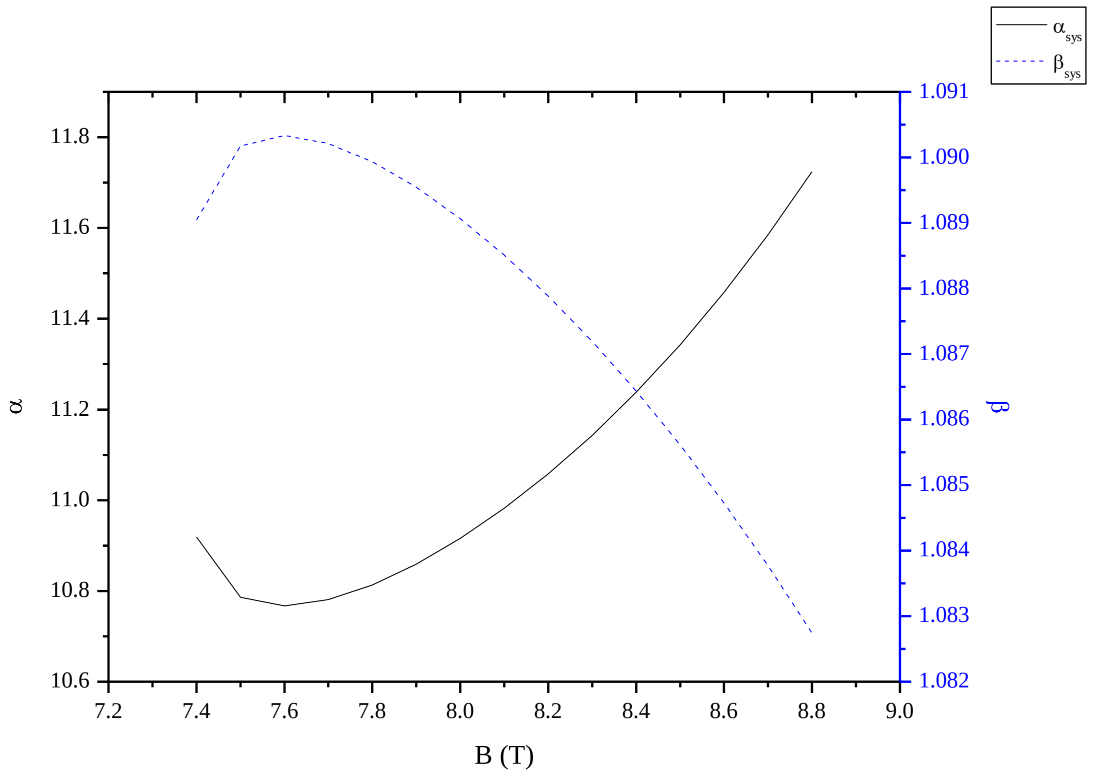

Fig.8. Variation of the exergy inefficiencies and sustainability indexes of the hybrid system with magnetic field.

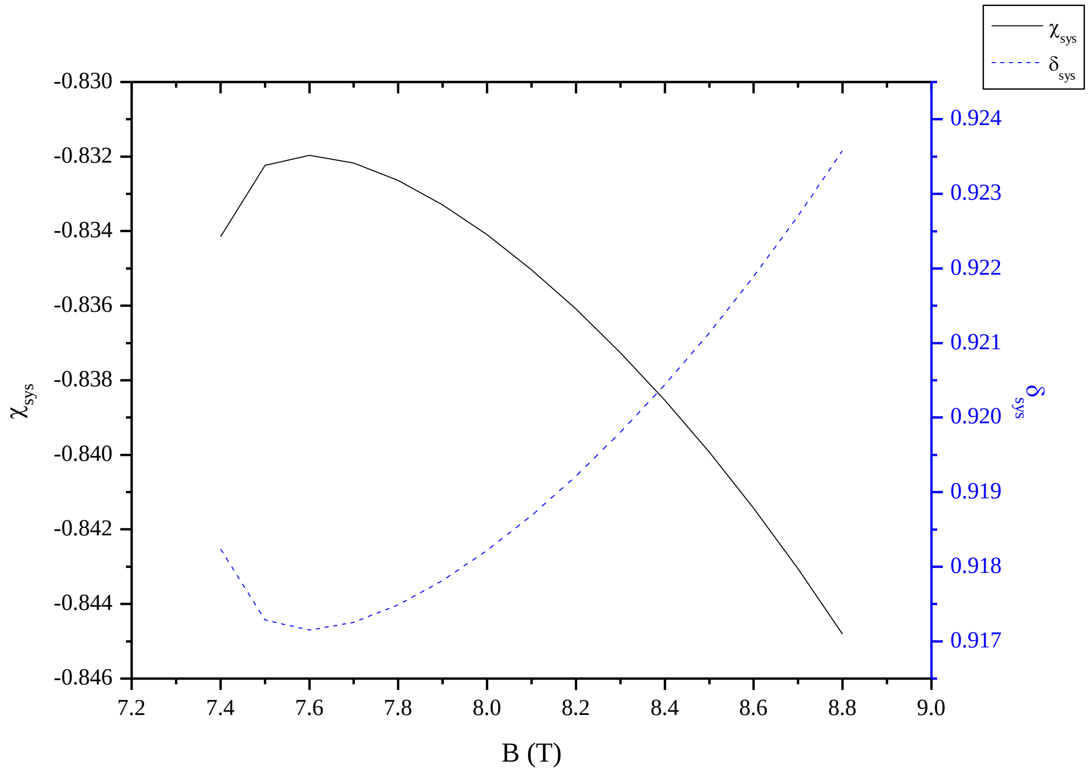

Fig.9. Variation of the exergetic ecological index and unavailability index of the hybrid system with magnetic field.

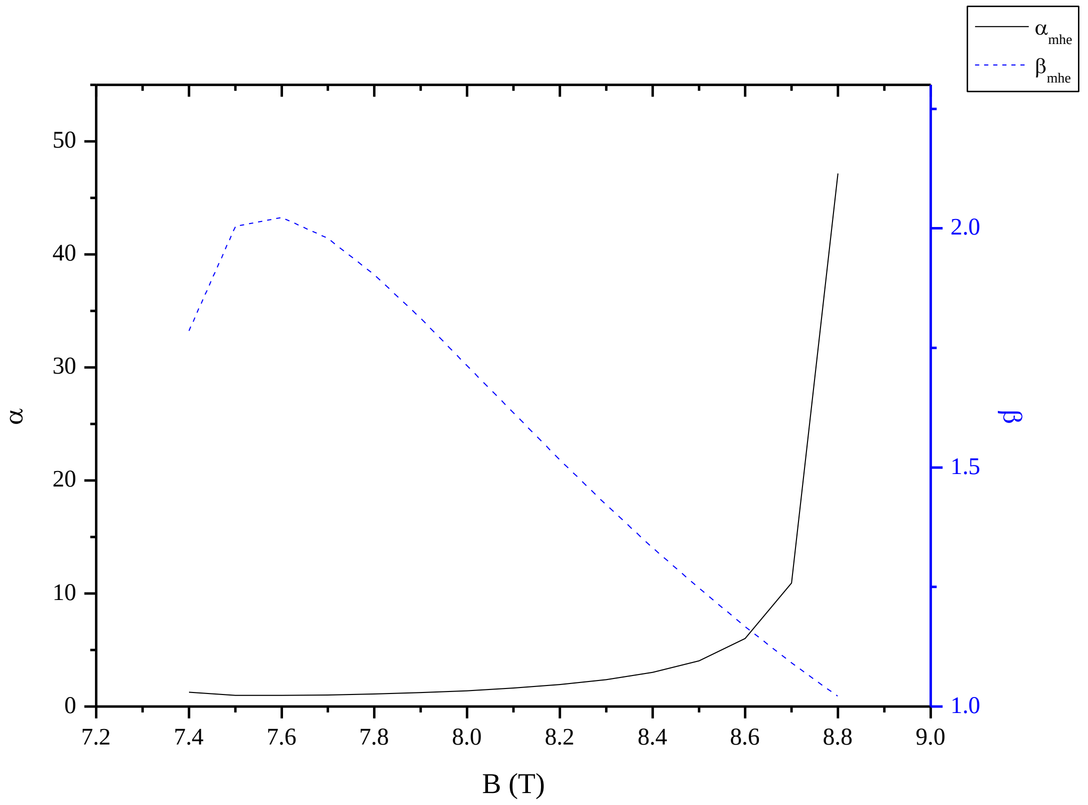

Fig.10. Variation of the exergy inefficiencies and sustainability indexes of magnetic heat engine with magnetic field.

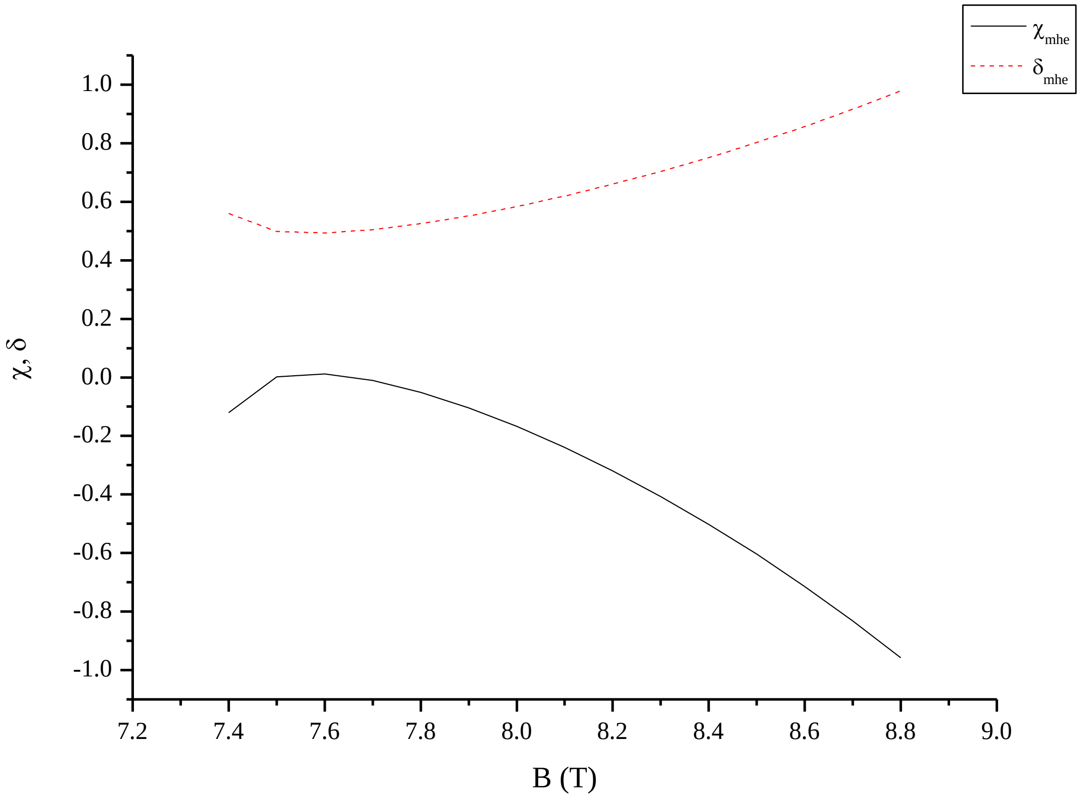

Fig.11. Variation of the exergetic ecological index and unavailability index of magnetic heat engine with magnetic field.