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Magnesium–Chlorine Cycle for Hydrogen Production Driven by Solar Parabolic Trough Collectors

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Abstract

The study analyzes an integrated Magnesium-Chlorine Mg-Cl thermochemical cycle with solar parabolic trough system. Direct solar radiations have been estimated with tilted and tracking collectors in the Algerian desert. The results reveal that, tilted tracking axis aperture toward the south at local latitude angle is most efficient than does fixed tilted aperture facing south per local latitude angle with an average difference of 0,9 MWh/m^2/year. Heat gain evolution from parabolic trough collectors is estimated to investigate heat sources. The best annual heat gain was observed in Tamanrasset with 7.919 and 19.99 MWh/m/year by fixed and tracking system, respectively. Hydrogen production rate from the process have been evaluated and compared under Algerian desert conditions. The maximum hydrogen production rate is obtained for Tamanrasset with 51,862 and 143,011 Ton H_2/year by fixed and tracking system, respectively.
Keywords: magnesium-chlorine thermochemical cycle, hydrogen production, solar parabolic trough collector.

Introduction

Hydrogen may play an important role as an energy carrier of the future [1]. It may be used as a fuel in almost every application where fossil fuels are being used today. Hydrogen combustion will be held without harmful emissions with an exception of NOx emissions. In addition, hydrogen may be converted into useful forms of energy more efficiently than fossil fuels. And despite public perception, hydrogen is as safe as other common fuels [2]. However, hydrogen is not an energy source. It does not occur in nature in its elemental or molecular form. Therefore, hydrogen must be produced. Hydrogen can be produced using diverse resources including fossil fuels, nuclear energy, and other renewable energy sources, such as solar, biomass, wind and geothermal using a wide range of processes.

Several reviews show that many researchers have focused their research on clean production of hydrogen in Algeria. R. Miri et al., 2007 [3] have presented design of a hydrogen generating station by water vapour electrolysis at high temperatures. The electricity supply is done by photovoltaic cells and the water vapour is ensured by a solar concentrating power station. Evaluation of the solar hydrogen production potential by water electrolysis in Algeria has been conducted by B. Negrou et al., 2011 [4]. The electricity supply is done by a solar tower power plant. The hydrogen production rate is given for

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various values of the solar radiation and several sites of Algeria. The feasibility of hydrogen production at high temperature electrolyser has been presented by H.Derbal-Mokrane et al., 2011 [5], using a hybrid parabolic trough concentrators to produce high temperature and a steam water and photovoltaic energy for electricity requirements. The production rate depends on geographic position, on climatic conditions and on sun radiation. N. Chennouf et al., 2012 [6]**,** have conducted an experimental study of photovoltaic solar hydrogen production system by alkaline water electrolysis in Ouargla city (Algeria). The **e**ffects of temperature and NaOH electrolyte concentration on hydrogen production have been examined. The potential of hydrogen production using an electrolyzer-concentrating photovoltaic system for different sites in Algeria has been evaluated by R. Boudries, 2013 [7]**.** For the system with the Fresnel reflector, the results show that the potential of the hydrogen production per unit cell area is about 0.14 kg H_2/m^2day for the least favorable month; while this value is about 0.19 kg H_2/m^2 day for the most favorable month. For the system with the parabolic trough reflector, these values are about 0.10 kg H_2/m^2 day for the least favorable month and about 0.17 kg H_2/m^2day for the most favorable month. D. Ghribi et al., 2013 [8] have investigated the technical potential for producing hydrogen from the PV/proton exchange membrane (PEM) electrolyser system. The system is composed of 60 W PV module connected with a commercial 50 W PEM electrolyser. The results show that the southern region of Algeria (Adrar, Ghardaia, Bechar and Tamanrasset) is found to have the relatively highest hydrogen production. The total annual production of hydrogen is estimated to be around 20–29 m^3 at these sites. Study of the CEVITAL hydrogen production unit has been carried out by R. Boudries et al., 2014 [9]. The unit, located in southern Algiers, is meant to produce high purity hydrogen by water electrolysis. A PV system for powering the hydrogen production unit was proposed. Results show that the system PV coupled with the hydrogen production unit is viable. A simplified methodology to evaluate the hydrogen production at three selected locations from Algeria using different wind turbine has been evaluated by M. Douak et al., 2015 [10]. The results indicate that the maximum value of hydrogen produced in different sites are: 76.12 tH_2/yr in Adrar using De Wind D6; 95.12 tH_2/yr in Hassi-R'Mel using De Wind D7; 84.48 tH_2/yr in Tindouf using De Wind D7. A technical and economic analysis for the implementation of molten salt cavity receiver thermal power plant in Algeria has been carried out by S. Boudaoud et al., 2015 [11]. Results show that the capacity factor and the levelized electricity cost have been found to be respectively of the order of 71% and 0.35 \$/kW_e. Hydrogen production from solar energy available in Biskra region in the east of Algeria by the Proton Exchange Membrane (PEM) electrolyzer has been conducted by A. Saadi et al., 2016 [12]**.** The electrolyzer is supplied by solar photovoltaic (PV) using three kinds of PV generator with rated power up to 6 kW. The adequate agreement between the simulation results and the experimental data verifies the effectiveness of the proposed models. H.Tebibel et al., 2017 [13] have presented mathematical model of hydrogen production by methanol electrolysis process using photovoltaic energy. Case studies were carried out on horizontal and tilted of PV array at 36° in Algiers site. Results reveal great opportunities of hydrogen production with 22.36 g/m^2 d and 24.38 g/m^2 d of hydrogen when using system with horizontal and tilted PV array position, respectively. S. Rahmouni et al., 2017 [14] have analysed the estimation of hydrogen production potential via water electrolysis with electricity produced from solar and wind energy in Algeria. The results give a total annual production of $2.4.10^5$ tons/ km^2 of solar hydrogen and $2.1.10^5$ tons/km^2 of wind hydrogen. In Adrar, Laghouat, Tamenrasset and Tindouf, at the south and southwest side of Algeria, it is seen the regions with the best potential production exceeding the estimated 8.10^4 tons/km^2/year of renewable hydrogen. The production of hydrogen using aqueous methanol solution as a feedstock and Solar PV as the energy has been considered by S. Menia et al., 2017 [15]**.** The potential of hydrogen production by electrolysis of aqueous methanol 4M solution has been estimated. It has been found that this potential is very important. S.K. Kirati et al., 2018 [16], have studied the influence of the electrolyzer operating conditions on the hydrogen production rates in the Adrar (Algeria) region using an alkaline electrolyzer fed by a renewable source in a hybrid energy system. The analysis shows that the increase in the rate of penetration of renewable energies induces a higher production of hydrogen which follows a nonlinear law as well as a better quality of the gases produced. A techno-economic study of hydrogen production using a hybrid solar gas power-electrolysis system in Algeria has been carried out by R. Boudries, 2018 [17]. The results indicate that the cost of hydrogen production is dominated by the cost related to the energy production and practically independent of the solar fraction. An energetic evaluation of a hybrid power plant has been made for the region of Djanet (East-South of Algeria), by M. Baik et al., 2018 [18]. The resources used are solar and wind energy. This study confirms that the Hydrogen hybrid system in the region of Djanet energetically is feasible to exploit the abundant solar radiation. M. Blal et al., 2018 [19], have compared energy potential of the wind and solar with the results of hydrogen production in various sites of Algeria. The simulation results show that the energy supplied by a photovoltaic module type UDTS 50 can supply energy for ten electrolyzer cells which are connected in series coupled this module. The results obtained showing that southern of Algeria has more hydrogen potential compared with the northern. The potential of hydrogen production in Algeria by an integrated copper-chlorine (Cu-Cl) thermochemical cycle with solar parabolic trough system has been estimated by M. Ouagued et al., 2018 [20]. Simulation results reveal great opportunities of hydrogen production using Cu–Cl cycle combined with solar PTC in the south of Algeria with annual hydrogen production exceeds 84 Tons H_2/year (around 0,30 kg/m^2/day).

Hydrogen production from thermochemical cycles using solar energy appears to be an eco-friendly and sustainable option for the countries having abundant solar energy resources as Algeria. The main energy input needed by such systems is high temperature heat. The Mg-Cl cycle is an hybrid thermochemical hydrogen production method which shows promising results in terms of maximum temperature requirement and electrical work consumption. This cycle can be coupled with several renewable resources (500-550ºC), and shows lower voltage requirement than that of conventional water electrolysis [21,22]. Feasible chemical reactions, mature electrolysis technology, and low maximum temperature of the cycle are promising in terms of integrating this cycle with solar energy sources.

Several works has been conducted to study the Mg-Cl thermochemical cycle, since 2012. M. Tolga Balta et al., 2012 [23], had presented energetic and exergetic analyses of the thermochemical cycle for hydrogen production. The results show that Mg-Cl cycle offers a good potential due to its high energy and exergy efficiencies as 63.63% and 34.86%, respectively based upon the conditions and parameters considered. H. Ozcan et al., 2014 [24]. had performed an Aspen Plus simulation to specify behaviors of reactants and products within hydrolysis and chlorination reactors of the Mg-Cl cycle for various temperatures, pressures, and steam/magnesium and chlorine/magnesium ratios. Results show that higher temperature and higher steam/MgCl2 ratio are required to provide full conversion of reactants in hydrolysis step. On the other hand, lower temperature, higher pressure and higher chlorine/MgO ratio are required to provide full conversion of chlorination reactor reactants. Modeling of an integrated solar based hydrogen production plant was performed by H. Ozcan et al., 2014 [25]. The proposed system consists of (a) a concentrating solar power cycle with thermal energy storage, (b) a steam power plant with reheating and regeneration, and (c) a hybrid thermochemical Mg-Cl hydrogen production cycle. The results show that the overall system energy and exergy efficiencies are found to be 18.8% and 19.9%, respectively, by considering a solar heat input. These efficiencies are improved to 26.9% and 40.7% when the heat absorbed by the molten salt is considered and used as a main energy input to the system. A study was undertaken by M. Tolga Balta et al., 2014 [26] to conduct energetic and exergetic analyses of a novel solar energy-based integrated Mg-Cl cycle for hydrogen production. The solar based integrated Mg-Cl cycle system considered consists of five subsystems, such as: (1) heliostat field subsystem, (2) central receiver subsystem, (3) steam generation subsystem, (4) conventional power cycle subsystem and (5) Mg-Cl subsystem. As a result, The overall energy and exergy efficiencies of the solar based integrated hydrogen production system 18.18% and 19.15%, respectively. H. Ozcan et al., 2016 [27]**,** had conducted an Aspen Plus simulations for the four-step Mg-Cl cycle with dry HCl capture. Results show that successful dry HCl capturing process makes this cycle 13% more efficient than water electrolysis, in terms of electricity consumption, and thermodynamically more efficient than the existing three-step configuration. An exergy based economic assessment of the four step Mg-Cl cycle was performed and compared with other hybrid thermochemical cycles by H. Ozcan et al., 2017 [28]. The results indicate that the final design of the Mg-Cl cycle shows lower hydrogen cost results than that of the Hybrid-sulfur Cycle and shows a similar trend with the hybrid Copper-Chlorine (Cu-Cl) cycle. MgO was utilized by H. Ozcan et al., 2018 [29] as the HCl capturing agent from an aqueous HCl in order to decrease the power consumption of the four-step Mg-Cl cycle. The results of these experiments show 30.8% HCl capture by solid MgO particles in a semi-batch packed bed reactor design with an uncertainty value of ±1.17%. The XRD results indicate that an optimum reactor temperature of ~275°C is critical to prevent the process from side reactions and undesired products.

In this study, hydrogen was discussed as a possible solution to storage energy from solar source. The three steps cycle configuration of the magnesium-chlorine cycle was simulated to determine the performance of the cycle. A thermal model was developed for relevant chemical reactions of Mg–Cl cycle for hydrogen production combined with solar parabolic trough collectors and testing its performance under Algerian desert.

2. Modelling

The proposed design of the system is shown in figure 1. It is integration between a conventional combined Mg-Cl thermochemical cycle for hydrogen production and solar field, based on parabolic trough solar collectors (PTC). We consider in this study a number of 100 Solar Collector Assembly (SCA) with 7.8 m in length divided on a loops of 20 SCAs to demonstrate the PTC performance under Algerian conditions. The proposed plant is presented in figure 1. The chosen collector is of LS-2 type with vacuum in the annulus space between the absorber and the glass envelope. The heat transfer fluid (HTF) considered in this study is Syltherm 800 designed for high temperature liquid phase operation with good heat transport and transfer properties. Ambient Conditions include direct solar irradiance, wind speed, ambient temperature from the selected location for clear days from different seasons of the year. Syltherm 800 is also suitable for use in heating and cooling systems with good thermal stability in application range and non-corrosive to materials of construction.

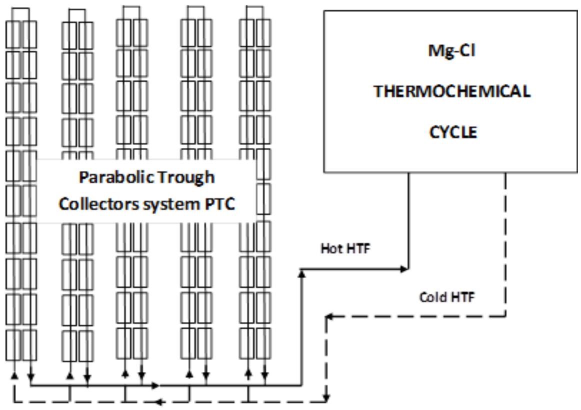


Figure 1**.** Schematic diagram of proposed system

Mg-Cl Thermochemical Cycle

The hybrid Mg-Cl cycle is three-step thermo-electrochemical cycle utilizing heat and electrical work to produce hydrogen. Main steps of the cycle are; the hydrolysis of $MgCl_2$, the chlorination of MgO, and the electrolysis of HCl gas [21,22]. The three steps reactions are presented in figure 2 and figure 3 [25]:

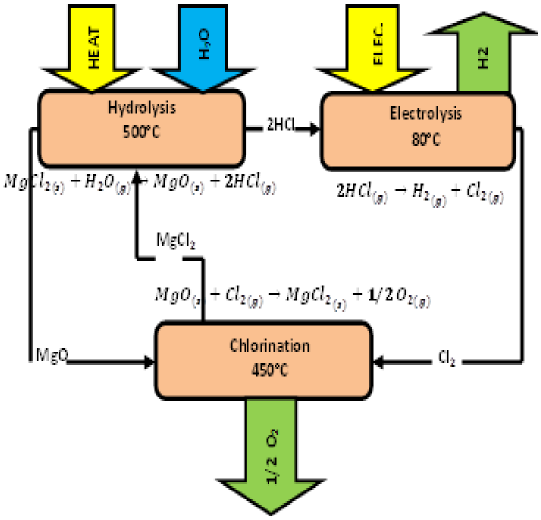


Figure 2. Three steps Mg-Cl reactions.

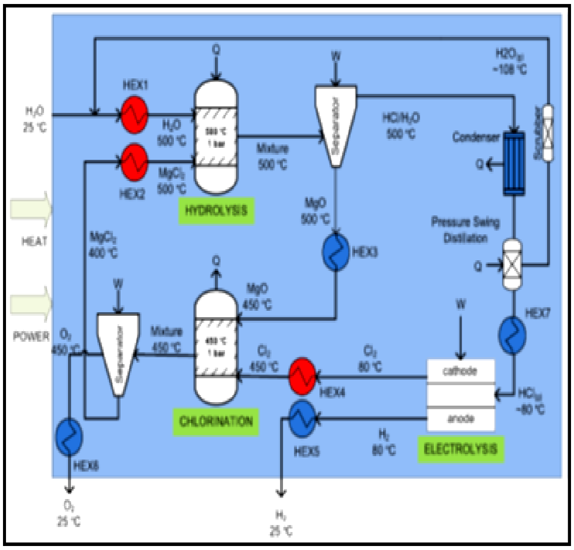


Figure 3. Schematic diagram of Mg-Cl cycle.

In the hydrolysis step, a solid gas reaction takes place, in which hydrogen chloride (HCl) and magnesia (MgO) are produced during the hydrolysis of magnesium-chlorine ($MgCl_2$). This reaction is endothermic and occurs at a steady-state. In this step, $MgCl_2$ is hydrolyzed to form MgO (s) and HCl (g) at about more than 450 °C. HCl (g), as the product of the hydrolysis process, enters the hydrogen production step to produce hydrogen and Cl_2 (g) [26].

In the chlorination step of Mg-Cl cycle, MgO(s) and Cl_2(g) enter the chlorination step as reactants to form $MgCl_2$(s) and oxygen at about reaction temperature of 400-500 °C. $MgCl_2$(s) is fed back to the hydrolysis step in order to form a closed internal loop that recycles all of the Mg compounds on a continuous basis [26].

In the hydrogen production step, hydrogen and chlorine can be produced thermochemically or electrochemically. Thermochemical dissociation of HCl is an energy-intensive process and reaction occurs at high temperatures. Compared to thermochemical dissociation, electrochemical process is a low temperature operation. Chlorine and hydrogen can be produced by electrochemically from anhydrous or aqueous HCl [26].

A thermodynamic analysis was performed to determine the heat released or absorbed by each step of the Mg–Cl cycle We consider in the study one mole of hydrogen produced per cycle, so all quantities are provided per mole of hydrogen produced. Also, we assume that:

- The reference environment temperature (T_0) and pressure (P_0) are 298.15K and 1atm, respectively.
- The chemical reaction reactants and products are at the reaction temperature and a pressure of 1atm.
- The process occurs at steady state and steady-flow with negligible potential and kinetic energy changes.
- The heat exchanger effectiveness is assumed to be 85%.

The energy balance for a steady-state reactions of hydrolysis and chlorination is [20,29-34]:

$$Q_i = \Delta H_i^{\circ}(T_0) + \sum n_{(i)product} \cdot (h - h_0)_{(i)product} - \sum n_{(i)reactant} \cdot (h - h_0)_{(i)reactant} \quad (1)$$

The enthalpy change of reactions at standard conditions $\Delta H_r^{\circ}(T_0)$ is given by Hess Equation:

$$\Delta H_r^{\circ}(T_0) = \sum n_i \cdot \Delta H_f^{\circ}(i)_{product} - \sum n_i \cdot \Delta H_f^{\circ}(i)_{reactant} \quad (2)$$

To calculate the enthalpy change of a substance that is cooled or heated over a particular temperature range without phase change, an isobaric process could be assumed and the enthalpy change can be calculated as [20,33-36]:

$$(h - h_0)_i = \int_{Ti}^{Tf} Cp_i \cdot dT \quad (3)$$

Where Cp_i (J/mol.K) is the specific heat of the substance based on a molar quantity and the subscripts on Ti and Tf are the initial and final temperatures, respectively.

In order to produce hydrogen from the process, heat exchangers are required to take the different compounds, used for each reaction of the cycle, to the desired temperatures. For the three steps Mg-Cl cycle, heat exchangers are needed; three exchangers for heating the compounds and four exchangers for cooling the compounds.

To calculate the heat or the enthalpy change of a substance that is cooled or heated in a heat exchanger over a particular temperature range without phase change, an isobaric process could be assumed and the enthalpy change can be calculated as follow [20,34,36-39]:

$$Q_{HEI} = n_i \left[\int_{Ti}^{Tf} Cp_i \cdot dT\right] \quad (4)$$

Where Q_{HEi} (kJ/mol H_2) is the heat in each exchanger, n_i the molar quantity of the substance and the subscripts on Ti and Tf are the initial and final temperatures, respectively.

Using the thermodynamic methods and specifying the operating conditions from experimental data in literature, the Mg–Cl cycle has been simulated. The model calculates the heat of reactions at the specified conditions. The heat, work requirements and other values for the processes at various transfer points are shown in Table (1).

The total heat requirement for the endothermic processes is 782.52 kJ/mol H_2 and heat recovery from the exothermic processes is 85.87 kJ per mol of hydrogen. For electrolysis step, the electrical energy requirement is given by Ozcan et al. [25], as 191.72 kJ/mol H_2.

Table 1. Energy balances of the Mg-Cl cycle

Step	Q_{in} (kJ/mol H_2)	Q_{out} (kJ/mol H_2)	Welec (kJ/mol H_2)
HCl production	702.86		
O_2 production		-50.34	
H_2 production			191.72 [25]
$HEX1$	48.82		
$HEX2$	4.1		
$HEX3$		-2.46	
$HEX4$	26.74		
$HEX5$		-1.59	
$HEX6$		-6.65	
$HEX7$		-24.83	
Cycle	**782.52**	**-85.87**	**191.72**

Hydrogen production rate

Based on results given in table 1, the capacity of the cycle combined with a parabolic trough solar thermal plant is evaluated. Using heat gain from PTC plant and Mg-Cl thermodynamic results, the hydrogen production rate is calculated from [20]:

$$R(H_2) = \frac{Q_{gain}}{Q_{in}} \cdot \frac{M(H_2)}{\rho(H_2)} \quad (5)$$

Heat Gain from Solar field

The heat transfer model is based on an energy balance between the fluid and the surroundings as presented by Ouagued et al., 2012, 2013 [40,41]. The global HTF heat gained per unit length of the receiver Q_{gain} (W/m) is given by:

$$Q_{gain} = \frac{F_f \cdot \rho_f \cdot C_f \cdot \left(T_f^{out} - T_f^{in}\right)}{L} \quad (6)$$

The model allows evaluation of the collector thermal efficiency. The collector thermal efficiency is represented by the ratio between global heat gain and direct solar irradiance [40,41]:

$$\eta_{col} = \frac{Q_{gain}}{Q_{sol}} \cdot 100 \quad (7)$$

To predict heat gain from parabolic trough collector under Algerian desert conditions, the climatic and topographical conditions specific to the area have been taken into account by exploiting the direct solar radiation. The Direct solar radiation, Q_{sol} *(W/m^2)*, the rate at which solar energy is incident on the aperture of a collector per unit aperture area, may be calculated from the beam radiation Q_{beam} and the angle of incidence Θi using the relation [40-46]:

$$Q_{sol} = Q_{beam} \cdot cos\ (\theta_i) \quad (8)$$

Θi: angle of incidence, (deg). Knowing this angle is of critical importance to the solar designer, since the maximum amount of solar radiation energy that could reach a collector is reduced by the cosine of this angle [20]. Two cases are studied in this paper to calculate the angle of incidence for fixed axis and single axis tracking apertures:

a. *For tilted fixed aperture facing south per local latitude angle*

$$\theta_i = \cos^{-1}(\sin\alpha \cdot \cos\beta + \cos\alpha \cdot \sin\beta \cos A) \quad (9)$$

b. *For tilted tracking axis toward the south at the local latitude angle:*

$$\theta_i = \delta \quad (10)$$

Hottel, 1976, has presented a method for estimating the beam radiation Q_{beam} (W/m^2) transmitted through clear atmospheres for a standard atmosphere [40,41,43,46-48]. Hottel's clear-day model of direct normal solar irradiance is based on atmospheric transmittance calculations for four different climate zones in the globe using the 1962 U.S. Standard Atmosphere [40,41,49,50]. The beam irradiance is given by:

$$Q_{beam} = I \cdot \tau_{beam} \quad (11)$$

To compare the importance direct solar radiation in different sites, seven locations from the Algerian desert were selected namely, Bechar, Ghardaia, Ouargla, Tindouf, In Salah, In Amenas and Tamanrasset as shown in figure 4. The geographical positions for each location are reported in table 2.

Figure 4. Algerian map with the seven selected locations [51].

Table 2. Latitude angle, longitude angle and altitude angle from mean sea level for different locations

Location	Latitude (deg)	Altitude (km)	Longitude (deg)
Bechar	31,38	0,806	-2,15
Ghardaia	32,48	0,500	3,66
Ouargla	31.67	0.152	6.15
Tindouf	27.7	0.433	-8.1
In Salah	27.2	0.265	2.47
In Amenas	28.05	0.6	9.63
Tamanrasset	22,47	1,378	5,31

3. Results & Discussion

3.1. Solar radiation

Using the insolation model and applying the appropriate sun angle calculations developed above, we can make hour-by-hour computations of the solar energy incident on the aperture of a collector. Figure 5 and figure 6 show the results carried out on two typical clear days from summer and winter for seven locations from Algerian desert. Figure 5 represents the direct solar radiation for fixed tilted aperture facing south per local latitude angle and figure 6 represent the direct solar radiation tilted tracking axis toward the south at the local latitude angle.

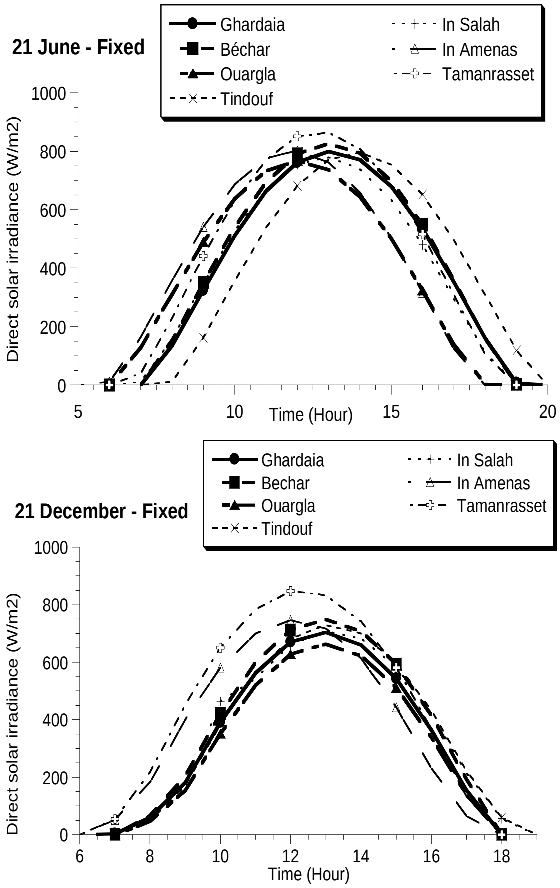


Figure 5. Direct solar radiation for fixed tilted aperture facing south per local latitude angle on June 21 and December 21.

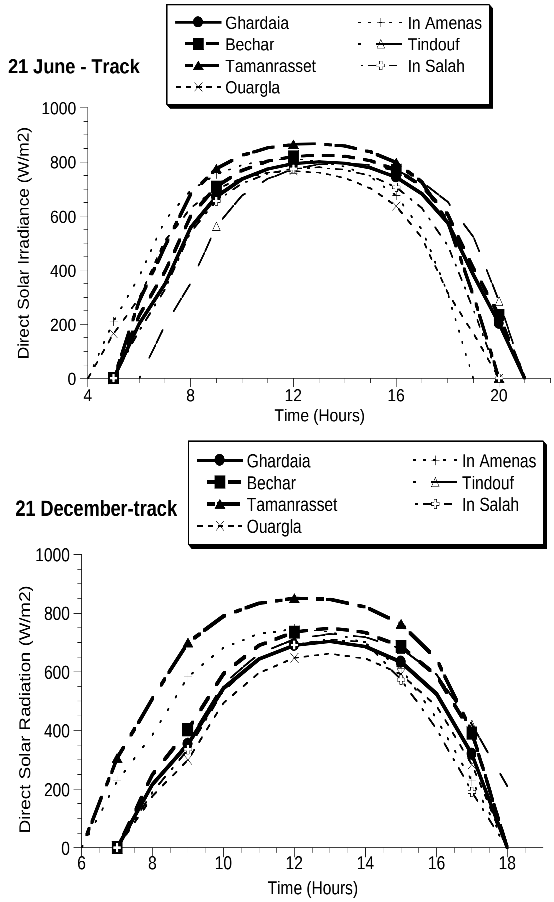


Figure 6. Direct solar radiation for tilted tracking axis toward the south at the local latitude angle on June 21 and December 21.

We notice a slight difference of direct solar radiation in the entire desert with both fixed and tracking system. In summer, direct solar radiation exceeds 850 W/m^2 for Tamanrasset, it exceeds 800 W/m^2 for Ghardaia, Bechar, In Amenas, Tindouf and In Salah, and exceeds only 750 W/m^2 for Ouargla. In winter, direct solar radiation exceeds 800 W/m^2 for Tamanrasset, it exceeds 700 W/m^2 for Ghardaia, Bechar, In Amenas, Tindouf and In Salah, and exceeds only 600 W/m^2 for Ouargla. Integrating throughout the typical days, we note that tilted tracking axis toward the south at local latitude angle receives more direct solar radiation compared to fixed tilted aperture facing south per local latitude angle. In summer, daily direct solar radiation variate in the Algerian desert between 5400 and 6000

W/m²/day for fixed aperture and variate between 8400 and 9700 W/m²/day for tracking aperture. In winter, daily direct solar radiation variate between 3900 and 5600 W/m²/day for fixed aperture and variate between 4800 and 7400 W/m²/day for tracking aperture. In table 3, the annual direct solar radiation is estimated and presented for the seven Algerian locations.

Table 3. Annual direct solar radiation for different locations in Algeria

Location	Annual Direct Normal solar Irradiance ($MWh/m^2/year$)	
	Fixed tilted aperture facing south per local latitude angle	Tilted tracking axis toward the south at the local latitude angle
Ghardaia	2.03	2.878
Bechar	2.14	3.083
Tamanrasset	2.36	3.451
Ouargla	1.9	2.657
In Amenas	2.107	3.048
Tindouf	2.059	2.904
In Salah	1.988	2.803

Taken over the entire year, tilted tracking axis aperture toward the south at the local latitude angle receives more energy than does fixed tilted aperture facing south per local latitude angle with an average difference of 0.9 MWh/m²/year. The best direct solar radiation is noticed in Tamanrasset with 2.36 and 3.451 MWh/m²/year by fixed and tracking system, respectively.

3.2. Parabolic trough collector system

In an integrated solar system, studying the effect of fluctuation in heat gain from this system is very important as heat gain is not constant throughout the day. Heat gain from PTC has been estimated for two typical days of summer and winter in the daylight period in clear sky in different locations with fixed and tracking system in figure 7 and figure 8.

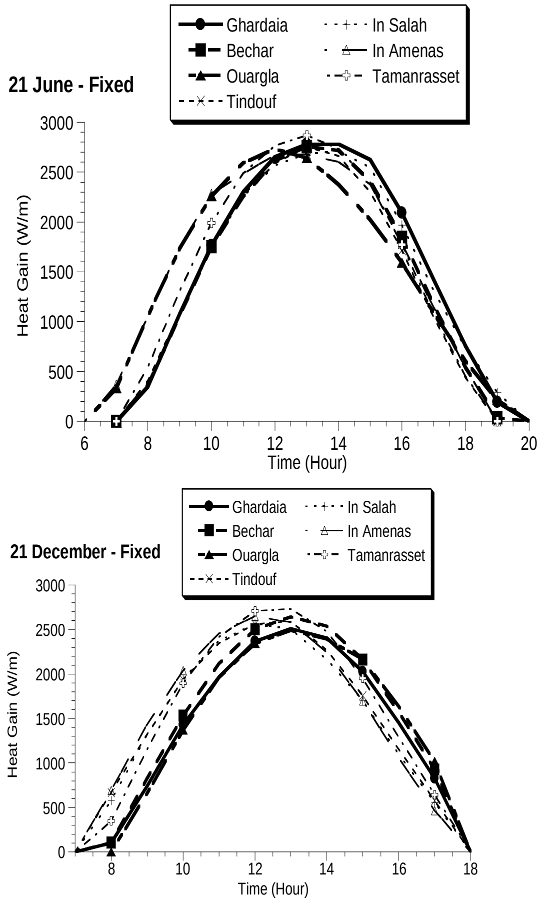
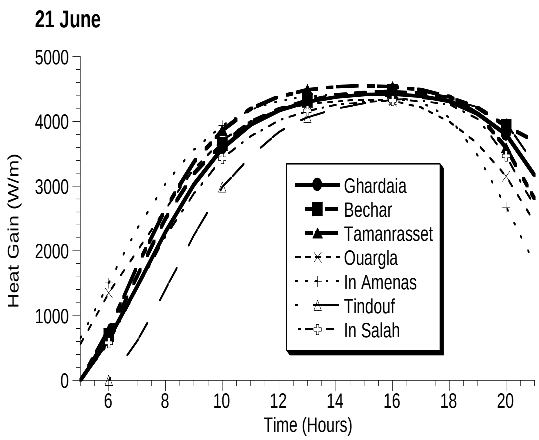


Figure 7. Heat gain in 21 June and 21 December for fixed tilted aperture facing south per local latitude angle system.



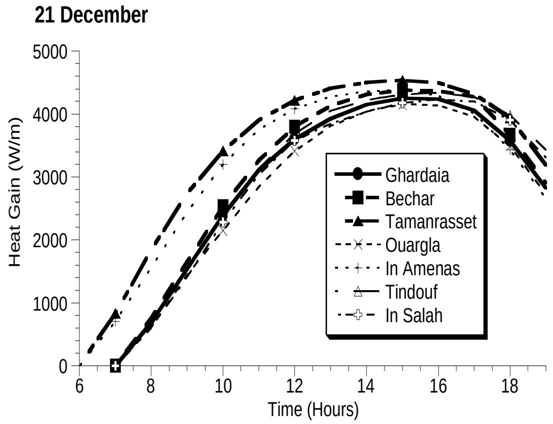


Figure 8. Heat gain in 21 June and 21 December for tilted tracking axis toward the south at the local latitude angle system.

We notice an important difference in heat gain from solar field in the selected sites with fixed and tracking system. The heat gain from solar tracking system is really important which exceeds 4000 W/m in southern Algeria for both summer and winter typical days. For solar fixed system, the thermal efficiency is less significant with a maximum heat gain exceeds 2500 W/m for both summer and winter. In Table 4, we present the annual heat gain by PTC system for the Algerian desert.

Table 4. Annual Heat Gain by PTC for different locations in Algeria

Location	Annual Heat Gain by PTC system (MWh/m/year)	
	Fixed tilted aperture facing south per local latitude angle	Tilted tracking axis toward the south at the local latitude angle
Ghardaia	7.281	18.604
Bechar	7.523	19.212
Tamanrasset	7.919	19.990
Ouargla	7.209	18.137
In Amenas	7.516	19.177
Tindouf	7.506	18.739
In Salah	7.336	18.303

The estimation of annual heat gain in the seven locations selected from the Algerian desert shows the influence of the solar radiation on PTC performance. The best annual heat gain was observed in increasing direct solar radiation locations which is noticed in Tamanrasset with 7.919 and 19.99 MWh/m/year by fixed and tracking PTC system, respectively.

3.3. Hydrogen production

The rate of hydrogen production by the combined Mg-Cl cycle and PTC power plant in the daylight period of two typical days of winter and summer is presented in Figure 9 and Figure 10.

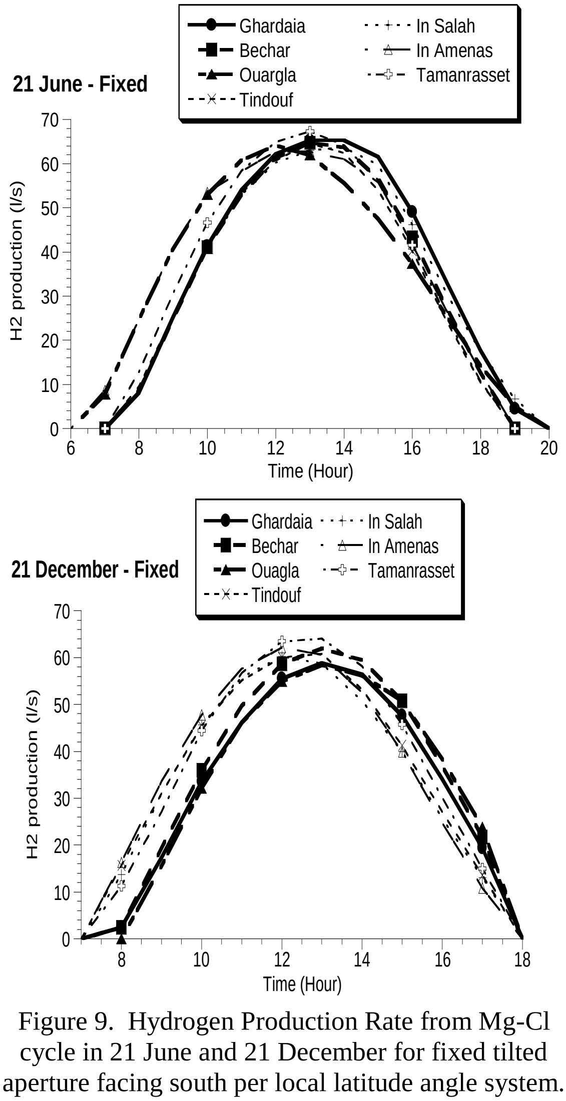
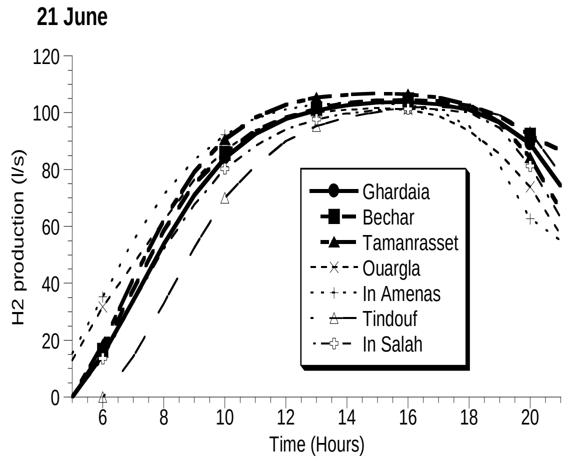


Figure 9. Hydrogen Production Rate from Mg-Cl cycle in 21 June and 21 December for fixed tilted aperture facing south per local latitude angle system.



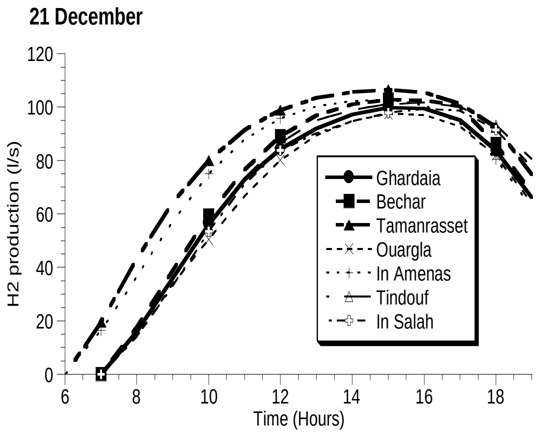


Figure 10. Hydrogen Production Rate from Mg-Cl cycle in 21 June and 21 December for tilted tracking axis toward the south at the local latitude angle system.

It is noticed form the results that the profile of the hydrogen production rate corresponds to that of the heat gain from the solar field. Hydrogen production rate exceeds 100 l/s from Mg-Cl cycle integrated with solar PTC equipped with tracking system. For fixed aperture collector case, hydrogen production reaches only 60 l/s. In Table 5, the annual hydrogen production is presented for the seven Algerian locations.

Table 5. Annual hydrogen production for different locations in Algeria

Location	Annual Hydrogen Production (Ton H_2/year)	
	Fixed tilted aperture facing south per local latitude angle	Tilted tracking axis toward the south at the local latitude angle
Ghardaia	44.826	132,440
Bechar	48.332	136,459
Tamanrasset	51.862	143,011
Ouargla	47.104	129,566
In Amenas	48.951	136,842
Tindouf	48.499	134,621
In Salah	47.804	130,259

The maximum annually hydrogen production is obtained for Tamanrasset with 51.862 and 143,011 Ton H_2 by fixed and tracking system, respectively. By tracking system, the annual hydrogen production is about 136 Ton in Amenas and Bechar, about 134,621 Ton in Tindouf, about 132,44 Ton in Ghardaia, and about 130 ton of hydrogen in both In Salah and Ouargla. Simulation results reveal great opportunities of hydrogen production using Mg–Cl cycle combined with solar PTC compared to other systems studied in the same climatic conditions.

4. Conclusion

A parametric study is conducted to investigate the effects of several operating parameters such as heat gain from the solar PTC equipped with fixed and tracking system on the rate of hydrogen produced. The results reveal that, for the concentrating solar plant, tilted tracking axis aperture toward the south at the local latitude angle is most efficient than does fixed tilted aperture facing south per local latitude angle with an average difference of 0,9 MWh/m^2/year. A comparative assessment is carried out to study the effect of different sites from Algerian desert on heat gain and hydrogen production rate from Mg–Cl. We obtained that the best annual heat gain was observed in increasing direct solar radiation which is noticed in Tamanrasset with 7.919 and 19.99 MWh/m/year by fixed and tracking system, respectively. These analyses have revealed that the rate of hydrogen production is proportional to the heat gain from the solar PTC. In addition, the maximum hydrogen production rate was obtained for Tamanrasset with 51.862 and 143.011 Ton H_2/year by fixed and tracking system, respectively, than for Bechar, In Amenas, Tindouf and In Salah.

Nomenclature

A	solar azimuth angle, (deg)
Cp_i	specific heat of the substance, J/mol.K
C_f	heat transfer fluid specific heat, (J/kg.K).
F_f	heat transfer fluid flow rate, (m^3/s)
$(h-h_0)_i$	molar enthalpy change of compound *(i)*, kJ/mol
I	extraterrestrial solar irradiance, outside the earth's atmosphere, W/m^2
L	Receiver length, (m)
M(H2)	Molecular weight of hydrogen, kg/mol
n_i	number of moles of compound *(i)*, mol
Q_{beam}	beam radiation, W/m^2
Q_{gain}	solar heat gained from the PTCs solar field, Watts
Q_{HEi}	heat in each exchanger, kJ/mol H_2
Q_i	heat flow into the hydrolysis step or chlorination step (negative for exothermic reactions), kJ/mole H_2
Q_{in}	heat requirement for the Mg-Cl endothermic processes, kJ/mol H_2
Q_{out}	heat recovery from the Mg-Cl exothermic processes, kJ/mol H_2
Q_{sol}	Direct solar radiation, *W/m^2*
R(H_2)	hydrogen production rate, liters (H_2)/s
T_f^{out}	HTF temperature at the output of the receiver, K
T_f^{in}	HTF temperature at the input of the receiver, (K)
Welec	electrical energy requirement for Mg-Cl cycle, kJ/mol H_2

Greek letters

$\Delta H_i^{\circ}(T_0)$	enthalpy change of hydrolysis step or chlorination step at standard conditions, kJ/mole H_2
$\Delta H_f^{\circ}(i)$	standard enthalpy of formation of compound (i), kJ/mole
ρ(H2)	density of hydrogen expressed on kg/liter
ρ_f	heat transfer fluid density, kg/m^3
η_{col}	collector thermal efficiency, %
Θi	angle of incidence, (deg)
τ_{beam}	atmosphere transmittance of beam radiation
β	aperture tilt angle from the horizon (β=latitude angle), (deg)
α	solar altitude angle, (deg)
δ	declination angle, (deg)

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