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Prospects of hydrogen production potential from renewable resources in Algeria

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ABSTRACT

Hydrogen production from renewable energies is a key part in the energy transition to realize a sustainable energy economy for both developed and developing nations. For Algeria, successful energy transition toward a hydrogen economy will require the establishment of its potential. This study was conducted to estimate the potential for producing hydrogen from renewable resources in Algeria. The renewable energies considered are: solar photovoltaic and wind. To accomplish this objective, first, we analyzed renewable resource data both statistically and graphically using Geographical Information System (GIS), a computer-based information system utilized to create and visualize the spatial distribution of the geographic information. Then, the study will evaluate the availability of renewable electricity production potential from these key renewable resources. The potential for the hydrogen production, via the electrolysis process with wind and solar photovoltaic electricity, is described with maps showing it per unit area in each region. Finally, the results of the estimated hydrogen potential from both resources for each region are compared and significant conclusions are drawn.

Introduction

The increasing dependency on fossil fuel for meeting the growing energy demands across the world has become a weakness in national economies. This is not only due to the finite reserves, but also due to their environmental impacts. Renewable hydrogen is a promising energy carrier for the future energy supply, its benefits as an environmentally friendly, versatile, and efficient fuel. Hydrogen may be produced from renewable energy sources through a variety of pathways and methods [1,2]. Attention around the world has focused on the promise hydrogen economy. In order to study the feasibility of the transition towards a hydrogen economy, as a major step we must evaluate, and estimate the potential of renewable hydrogen for each country. Geographical Information System (GIS) technology plays a crucial role in the potential analyses; it allows us to managing, analyzing, and displaying the spatial distribution of all forms of geographically referenced information.

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A number of studies in the literature have been widely discussed in the estimation of hydrogen production potential from key renewable resources using GIS in many countries in the world, which can be divided into two categories: regional and/or national scale. For regional scale, Dagdougui et al. [3] analyzed the hydrogen production potential by the electrolysis process in Liguria region at the north of Italy to regard the selection of locations with high hydrogen production based on the use of solar and wind energy sources. Sigal and co-workers [4] studied the natural resource and economic feasibility of the production and delivery of wind hydrogen in the province of Cordoba in central Argentina. Also, Esteves et al. [5] assessed the potential of hydrogen production in the state of Cearà, Brazil for the ammonia production purposes, via the Haber-Bosch process with electrolytic wind and solar photovoltaic hydrogen.

The largest number of studies are at national scale. In the United States, the assessment of hydrogen production from wind, solar, biomass, nuclear and hydropower is conducted by the National Renewable Energy Laboratory (NREL) [6–9]. Two studies by Posso have demonstrated the estimation of electrolytic hydrogen production potential from renewable energies in Venezuela [10] and Ecuador [11]. In Venezuela country, the electrolytic hydrogen potential has been evaluated based on solar photovoltaic, wind and mini hydro energies, though, in Ecuador the renewable energies considered were solar photovoltaic, wind, geothermal and hydropower. The potential for hydrogen production from three major renewable resources (wind energy, solar energy and biomass) in Argentina was analyzed by Sigal et al. [12].

Algeria with an economy fully dependent on hydrocarbon incomes is not an exception to the rule and is also concerned about energy substitution even with many underestimated and unexplored energy resources. In the medium term, the development of the above mentioned vision, i.e. combination of renewable and hydrogen will obey to an economic necessity rather than to policy considerations. The decentralized nature of renewable makes them economically viable for the development of a territory composed essentially of more than 85% of arid zones and low population density. Moreover, Algeria has to face many challenges on medium and long terms. The first one, is on a national level, and comes from a constant increase in energy demand issued from a high population growth. The second one, is on an international level, and is basically linked to energy export and a safe, security supply of the Mediterranean region [13]. The energy transition from traditional fossil fuel based economy towards a sustainable hydrogen economy by estimating the renewable hydrogen amount has the potential to solve all major energy challenges that confront Algeria today; reducing dependence on oil and gas sector, reducing greenhouse gas emissions and meeting its policy goals. The hydrogen could play an increasingly important role in Algeria's energy future by its use both; as an energy carrier or major transportation fuel [14].

In a previous research the potential for producing hydrogen was analyzed from geothermal resources in Algeria [15]. In this work, the area of analysis is extended to explore two other main renewable energy resources in the country: solar and wind. The main objective of this study is to assess and provide a comprehensive picture of hydrogen production potential by water electrolysis process using solar and wind energies in Algeria. To accomplish this, we briefly describe the energetic situation in Algeria, including an analysis of the water and renewable energy resources. Then we present the followed method to investigate the wind speed and solar irradiation in Algeria. GIS tool, more specifically, an ArcGIS Spatial Analyst is used to produce maps of wind and solar energy. Therefore the electrical potential is calculated and presented after the introduction of the meteorological results in the photovoltaic and wind turbine models. The potential of hydrogen production by solar and wind energy is analyzed both statistically and graphically using GIS, where the aim is to highlight suitable regions that have high annual hydrogen production from solar and wind energies. Finally, a comparative study between solar and wind hydrogen production potential is presented.

The Algerian energetic context

Renewable energy projects

Algeria's energy mix is almost exclusively based on hydrocarbons, mainly NG (93%). The small share of renewable energy is currently dominated by hydropower. The oil and gas alone provide more than a third of Gross Domestic Product (GDP) (36% in 2013), 70% of government revenue and 97% of exports [16]. The heavy dependence of the economy on the oil and gas sector is a potential source of vulnerability for the Algerian economy and points to the need to revamp the policies and programs aimed at diversifying sources of growth in Algeria. Also, Algeria is very well placed to be a major player in the lucrative market of renewable energy. However, the transition to more renewable energy use will need to start immediately with the implementation of adequate policies regarding energy strategy and sustainable development programs.

Algeria has a nationwide environment strategy, a national plan for environmental action and sustainable development (*Plan national d'action environnementale et de développement durable*, adopted in 2002) [17], focusing on reducing pollution and noise, preserving biodiversity and natural spaces, training and raising of public awareness on environmental issues. To face the territorial disparities in Algeria and to create conditions for sustainable and harmonious growth countrywide, a national development plan (*Schéma national d'aménagement du territoire*, SNAT, adopted in May 2010) sets out the long-term vision between now and 2025, aimed at gradually reducing regional inequalities and enhancing the attractiveness of areas lagging behind in development [18].

The integration of renewable energies into the national energy mix constitutes a major challenge in the preservation of fossil resources, the diversification of electricity production ways and the contribution to sustainable development. The National Program for the Development of Renewable Energy 2011–2030 (*Programme national de développement des énergies renouvelables*) adopted by the government in February 2011. This program saw a first phase dedicated to the achievement of pilot and test projects of the different available technologies, during which relevant elements

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concerning technological evolutions in the concerned sectors appeared in the energy arena and led to the review of this program.

The renewable energy program aims to use extended renewable sources, mainly solar power and photovoltaic systems and, to a lesser extent, wind power. It provides to install 22 GW (between 2011 and 2030) which represents 40% of whole energy consumption from renewable source by 2030 [19]. The review of this program is on the large-scale development of photovoltaic and wind fields, on the introduction of biomass field (waste valuation), of the cogeneration and geothermal, and also the postponement, to 2021, of the development of the solar thermal (CSP). The renewable consistency of the program to realize for national market needs over the period 2015–2030 is 22 GW, among whom more than 4500 MW will be realized before 2020 [20]. The objectives of the new renewable energy program in Algeria are shown in Fig. 1. Achieving this program will allow to reach by 2030 a part of renewable of about 27% in the national report of electric production.

Hydrogen production projects

Hydrogen has the potential to solve all major energy challenges that confront Algeria today. Therefore, in Algeria, the transition toward a hydrogen economy has already begun. During the First International Workshop on Hydrogen: energy vector of renewable origin organized in Algiers, Algeria in June 2005, many recommendations were suggested developing hydrogen economy by research, demonstration, education, and outreach activities. The main recommendations are the creation of The Algerian Hydrogen Association (2AH2), and the launch of a large Maghreb-Europe cooperation project [21].

The Mediterranean Hydrogen Solar (MedHySol) is a project for the development of a massive solar hydrogen production and its exportation. Two steps will assure the achievement of this project. The objective of the first step is to realize a technological platform allowing the evaluation of emerging technologies for hydrogen production from solar energy with a significant size (10–100 kW) and to support the development of energetic rupture technologies. The second step of the project is to implement the most effective and less expensive technologies to pilot great projects (1–1000 MW) [22].

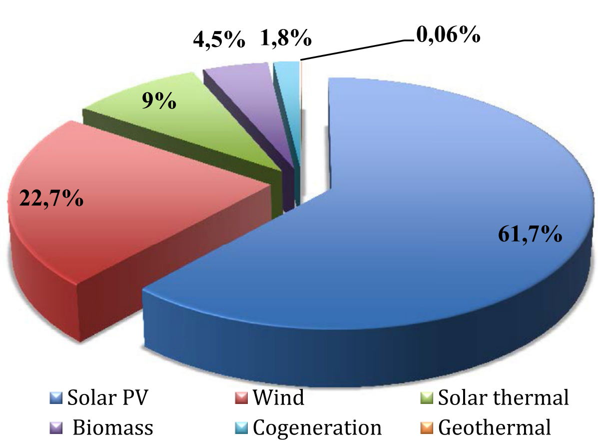

Fig. 1 – Objectives of the updated renewable energy program in Algeria by 2030.

In order to transition toward hydrogen as an alternative transportation fuel, Algeria has been implemented Hydrogen–Solar–Methane (HySolThane) project (as part of the MedHySol project, which is applied on transportation sector). This project intended for the development of Hydrogen enriched Compressed Natural Gas (HCNG) fuel road with 8% by volume of Hydrogen in NG for several tens of bus in the city of Algiers and to extend the operation to the other big cities of Algeria before 2020. The principal goal of this project is to plan a roadmap for the introduction of hydrogen in the energy economy in Algeria based on Compressed Natural Gas (CNG), in which technology such as the H_2-Internal Combustion Engine has an important role in the short and medium term [23].

Water resources

Beyond its largest renewable energy sources, Algeria has huge reserves of groundwater hydraulics resources in which it has the ambition to develop with international partners many projects for development of the massive renewable hydrogen production [22]. Algeria, with a surface of 2.4 million km^2, is the largest country of northern Africa. The major part of the country (87%) corresponds to a desert, where precipitations are quasi null, but which conceals important fossil underground water resources. The Northern part of the country is characterized by a Mediterranean climate, with renewable surface and underground water resources. Ninety percent of the surface water is located in the Tell area which covers about 7% of the territory. In the southern Saharan region, groundwater comprises mainly fossil water with negligible recharge. Although six main aquifers have been identified the bulk of water resources are contained within two major confined aquifer systems; the Terminal Complex (CT) and the Continental Interlayer (CI). These aquifers are jointly exploited with Libya and Tunisia and together they form the Septentrional Saharan Aquifer System (SSAS). The annual amount of rain is 100 billion m^3, of which 80% evaporates into the atmosphere. The water resources are estimated at 19.1 billion m^3/year, of which 12.4 billion of surface water and 6.7 billion of underground water. Only 6 billion could be mobilized by dams. For the moment only 4 billion are mobilized by nearly 110 dams. From the 6.7 billion of ground water resources, 5.1 billion are located on Sahara. The rest, 1.6 billion m^3, is already mobilized at a rate of 80%, principally by wells and boreholes [24,25].

Methodology to assess the available renewable resources potential

The first step to evaluate the hydrogen production using renewable energies is the analyzing of solar and wind potential in Algeria. For this, we will focus in this section on the methodology followed to assess the potential of each renewable energy resource, which is different due to the varied nature of the source, and due to the geographic site specification, climatic conditions and technological limitations of each source.

The determination of the available wind and solar potentials in the whole territory is based on the data of the meteorological measurement stations which are not sufficient to estimate the wind and solar potentials in other locations where no measurement stations are available. A spatial interpolation technique is used to predict the wind speed or solar irradiation in locations where data are not available. A variety of spatial analysis methods are available to interpolate the values of meteorological phenomena. For this reason, prediction methods are needed in order to predict the wind and solar potential for each point of the territory. An interpolation method is required to find out the potential accessible anywhere in the country. Numbers of method are available to construct an interpolated surface between available point's data measurement. In this analysis, the method used to convert the point data into raster format is the Inverse Distance Weighted (IDW). IDW interpolates a raster surface from points using an inverse distance weighted technique. It determines cell values using a linear weighted combination of a set of sample points [26]. It is easy and straightforward to interpret, it is based on the idea of the assumption that the attribute value of an undefined point is the weighted average of known values within the neighborhood points, and the weights are inversely related to the distances between the sampled points and the ones to be predicted.

Once the renewable energy potential of each region is interpolated using the IDW method, a geographical representation of the resulting potential from solar and wind is mapped using the ArcGIS software. This software is a computer system for capturing, storing, checking, and displaying data related to positions on the Earth's surface [27].

Solar resource analysis

Today, the most common technologies for utilizing solar energy are photovoltaic and solar thermal systems. One of the main influencing factors for an economically feasible performance of solar energy systems (besides of installation costs, operating costs and lifetime of system components) is the availability of solar energy on ground surface that can be converted into heat or electricity. Hence, precise solar irradiation data are of utmost importance for successful planning and operation of solar energy systems. Solar irradiation means the amount of energy that reaches a unit area over a stated time interval. The amount of solar irradiation varies regionally with the changing seasons, and hourly due to daily variation in sun's elevation.

In this study, to develop a solar irradiation map for the region the solar database given by Solar Atlas for the Mediterranean (Solar-Med-Atlas) is used, which is a free online database, and is a portal for historical, annual and monthly averages of global horizontal irradiation (GHI) and direct normal irradiance (DNI) data for the southern and eastern Mediterranean regions.

The Solar-Med-Atlas is integrated into a web system and developed under a project supported by the International Climate Initiative of the Germany Ministry of Environment, Nature Conservation and Nuclear Safety supports. The project brings solar resource data, with high resolution (1 km), long term coverage (20 years 1991–2010) where Global Horizontal Irradiation and Direct Normal Irradiation are derived from the Meteosat satellites and atmospheric data, and they are validated with the existing ground measurements in the region, covering the countries: Algeria, Egypt, Israel, Jordan, Lebanon, Libya, Mauretania, Morocco, Palestinian National Authority, Syria, Tunisia and Turkey. The databases are freely accessible and available via online information system and provide access to annual values, long-term monthly averages, and support information for any location in the target region, which ensures effective access to the data [28].

As shown in Fig. 2, an important potential of solar energy is available and differs remarkably in Algeria. The total annual solar energy on a horizontal plan of one square meter is approximately 2 MWh over the major part of the national territory. In addition, it seems that southern regions are more promising than others for the exploitation of solar resources for hydrogen production. In particular, Tamenrasset and Illizi have a high annual solar energy potential, which correspond to 2.4 and 2.2 MWh/m^2, respectively. The minimum amount of annual solar energy available reached on the coastal line as well as in some northern region sites; especially in Jijel, El-Taref and Blida, which is around of 1.6 MWh/m^2.

Wind resource analysis

The knowledge of the characteristics of the wind regimes in any locations given by the meteorological measurement stations is important in the exploitation of wind resources. Recently in Algeria, a contribution to improve the wind map in Algeria was made by Boudia et al. [29], using more recent meteorological data, collected at 63 measurement points distributed over the Algerian territory and 24 in neighboring countries close boundaries, these data were obtained at a height of 10 m, and recorded for a period of 10 years (2001–2010). We should note that, the wind speed increases with the height of wind turbines above ground level, this means that all turbines with hub heights than 10 m (which is all currently available wind turbines) will see a significant increase in annual mean wind speed.

The wind speed measurements are obtained from the Algerian Meteorological National Office are pieces of single point information at each measurement station. The data were collected with different periods for each site and used to evaluate the annual frequency of wind speed and annual variations of the average wind speed. After this, wind speeds were interpolated with the IDW. The Inverse Distance Weighting Method (IDW) is a geospatial interpolation, which puts pieces of single point information into a relationship. Thus, the highest and lowest values mark the range for the average. The relation between two points is assumed to decline the further the distance of the points. The output of the space between being a continuous raster information with values between the highest and the lowest input wind speeds in this study. The procedure for calculating the IDW in ArcGIS is to take the wind speed point information as input and then choose the z-value of the wind speeds measured. The output

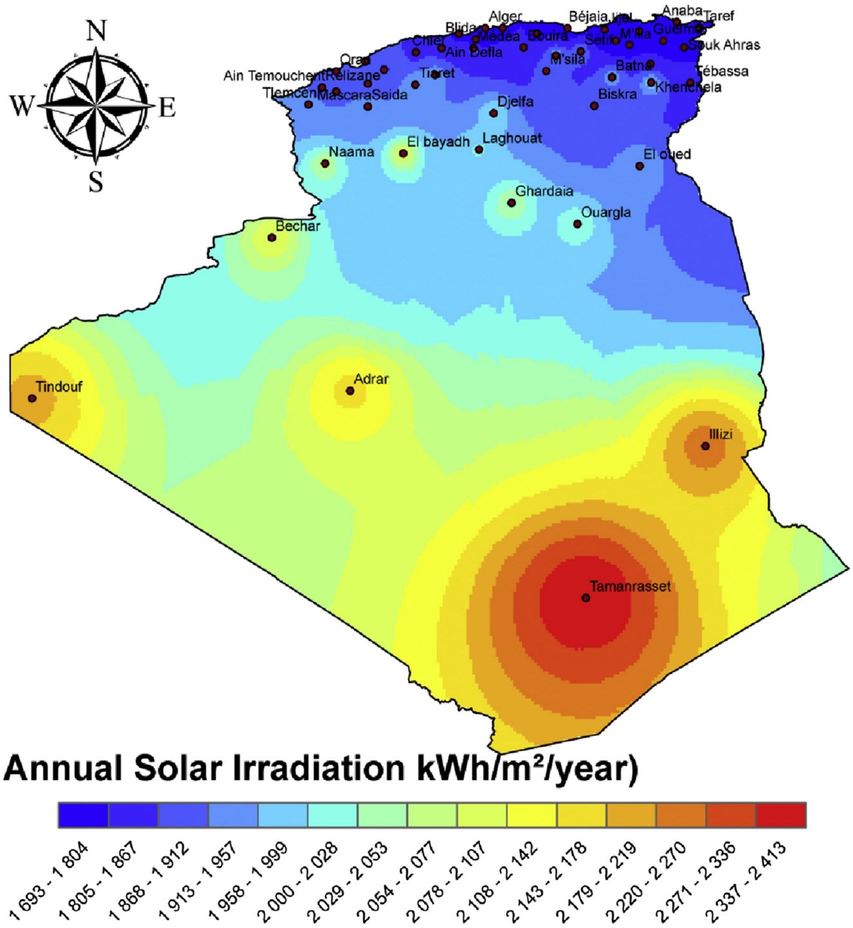

Fig. 2 – Annual average of the global horizontal solar irradiation in Algeria.

cell size is then set 0.072 (Decimal Degree) (default was set on ~0.056, so the next highest cell size (DD) was set). The other optional functions were left as default [27].

In this study the wind speed estimates from this database at a height of 10 m. The wind map in this section was made by GIS software, the annual wind map of Algeria, at a height of 10 m, is presented in Fig. 3.

Fig. 3 shows the annual average wind speed of each region. From the wind speed analysis, it can be observed that the mean wind speed for Algeria varies from 1.6 m/s to 6.3 m/s. The highest wind speeds recorded are: 6.3 m/s for the region of Adrar, 6.1 m/s for Hassi-R'mel and 6 m/s for Tindouf region. The attractive windy regions are located in the southwestern areas and in Tiaret, Borj-Baji Mokhtar, Djelfa and Biskra. The average wind speed in the coastal line region is about 4 m/s. The lowest speed of 1.6 m/s was observed for the region of Tizi-Ouzou (northern region). So for the Maghnia region (northwestern region), we observe that the wind potential is below 1.4 m/s.

Modeling electricity production potential

The estimation of hydrogen production using renewable energies in Algeria depends primarily on the estimation of the electricity production potential of wind and solar energies, this estimation is based on the introduction of the collected solar irradiation and wind speed data in specific mathematical models to obtain the electrical potential distribution in Algeria. This process is achieved using Excel spreadsheets, in order to assess the electrical production potential.

Modeling of photovoltaic panels

Photovoltaic panels generate electricity directly from sunlight via an electronic process that occurs naturally in certain types of material, called semiconductors. Electrons in these materials are freed by solar energy and can be induced to travel through an electrical circuit, powering electrical devices. The annual energy produced by the photovoltaic panel can be expressed as follows [30]:

$$E_{PV} = \eta_{PV} * \eta_{PG} * G \quad (1)$$

G Annual horizontal solar irradiation, kWh/m^2/year
η_{PV} Module reference efficiency, %
η_{PG} Power conditioning efficiency, %

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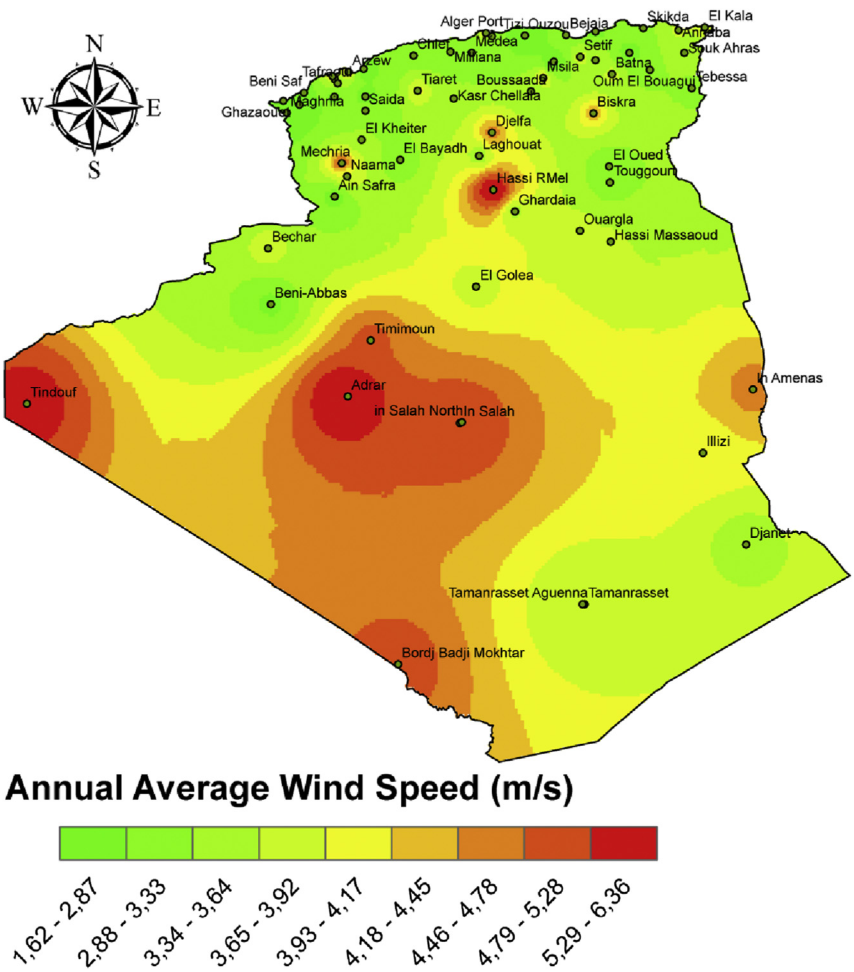

Fig. 3 – Annual average of wind speed at 10 m above ground level in Algeria.

Wind turbine model

The power contained in the wind as a kinetic energy P (kW) is expressed as [31]:

$$P = \frac{1}{2} * \rho * A * V^3 \quad (2)$$

A Swept surface of the wind turbine, m^2
ρ Density of air, kg/m^3
V Wind speed, m/s

The wind turbine can recuperate some of the kinetic energy of the wind, and it represents the power generated by the wind turbine:

$$P_{el} = \frac{1}{2} * \rho * C_e * A * V^3 \quad (3)$$

C_e Efficiency factor, which depends on the wind speed and architecture of the system.

It is determined from the performance of the transformation unit:

$$C_e = C_P * \eta_m * \eta_g \quad (4)$$

C_P Coefficient of performance of the wind turbine ($C_{P-max} = 0.593$)
η_m Efficiency of the gearbox, %
η_g Efficiency of the generator, %

In this study, we take $C_e = 0.45$. Therefore, the energy generated by the wind generator is expressed by:

$$E_{el} = P_{el} * \Delta t \quad (5)$$

Estimation of renewable electricity production

Solar electricity production analysis

To estimate the electrical energy potential, it was considered mono-crystalline photovoltaic panels with a power of 250 W at peak, and an efficiency of 15.28% [32]. The spatial distribution of power generated from solar energy is presented in Fig. 4.

The results show that all territory of Algeria can produce a comprehensive amount of solar electricity varies between 250 and 370 GWh/km^2 annually. Tamenrasset region maintains its supremacy in terms of maximum electricity potential with

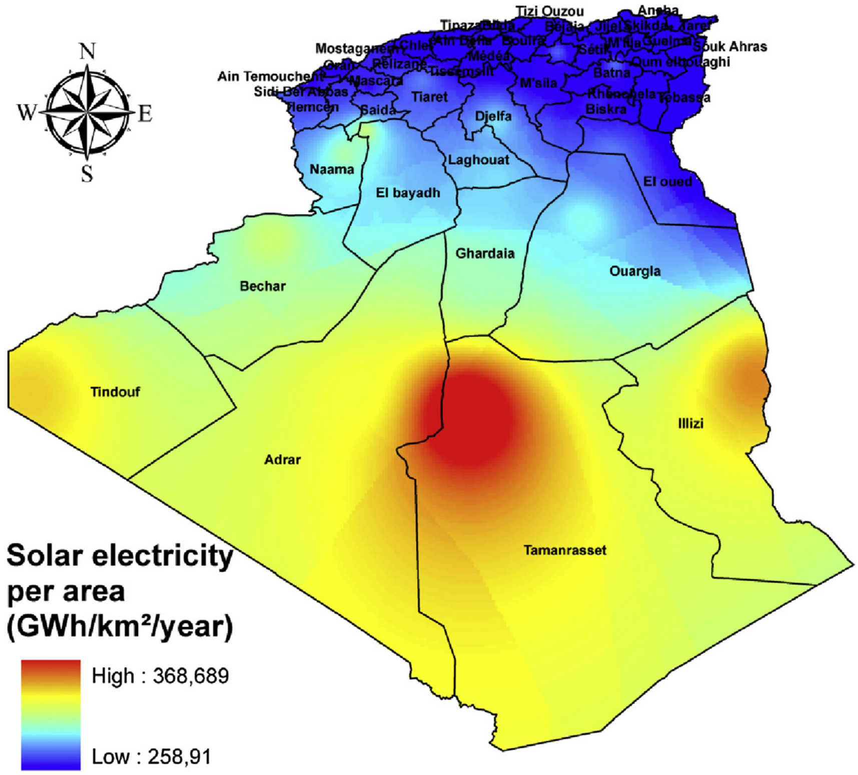

Fig. 4 – Solar electricity production.

368.7 GWh/km^2/year. Followed by the region of Adrar with 328.9 GWh/km^2/year. The site of Bechar in the extreme west of the country takes the third place with and annual mean solar power production of 321.1 GWh/km^2/year. The evaluation of the solar electricity production shows high potential of solar energy exploitation widely observed in the south of the country, when a large scale hydrogen production from solar energy is largely recommended.

Wind electricity production analysis

The electrical energy results obtained from the wind turbine model of 1.5 MW rated power are presented in Fig. 5. As seen, wind electricity potential is irregularly dispersed throughout the territory. The Southern part of Algeria is considered as regions with high electricity potential, and we can be seen scattered in the southwest as well as in the central region.

The highest annual mean wind electricity production is estimated in Hassi R'mel region (Laghouat) with 1074.8 GWh/km^2, while the lowest value is given in the site of Tizi-Ouzou, equal to 48 GWh/km^2/year. The estimated electricity production from wind turbines in the rest of the country varies in less than 900 GWh/km^2 yearly, which remains highly respectable and promotes wind electricity exploiting.

Hydrogen potential from renewable energy

Renewable energies are a desired energy source for hydrogen production due their diversity, abundance, and potential for sustainability. Renewable hydrogen is mainly an economic option in countries with a large renewable resource base and/or a lack of fossil resources, for remote and sparsely populated areas or for storing surplus electricity from intermittent renewable energies. Hydrogen can be produced by splitting water into its constituent elements using a process known as electrolysis, which requires electricity.

One advantage of electrolysis of water is that compatible with a large variety of available renewable energy technologies, namely, solar, hydro, wind, wave, geothermal, etc. In addition, water electrolysis benefits of some additional advantages, among them the use of different scales (on-site and off-site), its greater maturity, compactness and high current density and smaller footprint.

Renewable hydrogen production installation

A system of hydrogen production from renewable power has been proposed in this study. It consists of a renewable energy sources, an AC/DC converter and a Polymer Electrolyte Membrane (PEM) electrolyzer (see Fig. 6). In this system, the AC output of the sources is converted to a DC voltage suitable for electrolysis operation through an AC/DC converter. In fact, the electricity generated from renewable sources can be turned into hydrogen using the electrolysis process; hydrogen can then be stored until it can be transferred into electricity.

Electrolysis modeling

The generated solar and wind energy is sent to the electrolyzer to drive the electrolysis process of water. The results of

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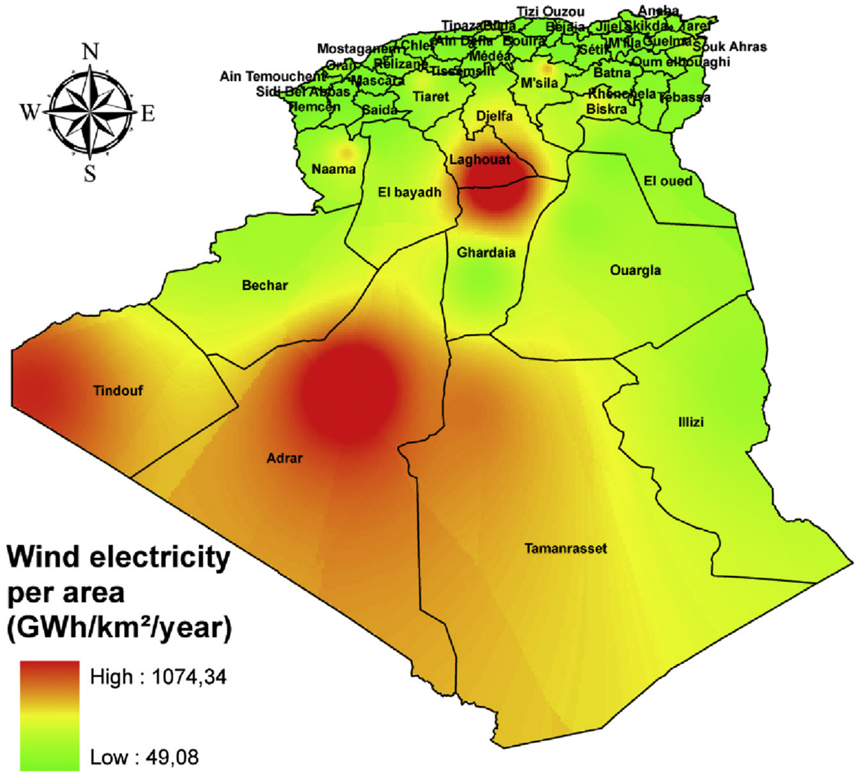

Fig. 5 – Wind electricity production.

this study are based on the use of a proton exchange membrane electrolyzer (PEM). PEM electrolysis is a viable alternative for the generation of hydrogen in conjunction with renewable energy sources. it can generate hydrogen (and optionally oxygen) at pressures up to 200 bar, with very little additional power consumption, which may be attractive for the application where hydrogen needs to be stored or used at elevated pressure [33]. For this, we consider an electrolytic production rate of 52.5 kWh/kg of hydrogen (which is equivalent to about 75% in efficiency). The energy transferred to the electrolyser is defined as [30]:

$$E_{H_2} = \eta_1 * \eta_2 * E_{RES} \tag{6}$$

η_1 Electrolyser operation efficiency, %
η_2 Electrolyser losses, %
E_{RES} Renewable electric source production, kWh/km^2/year

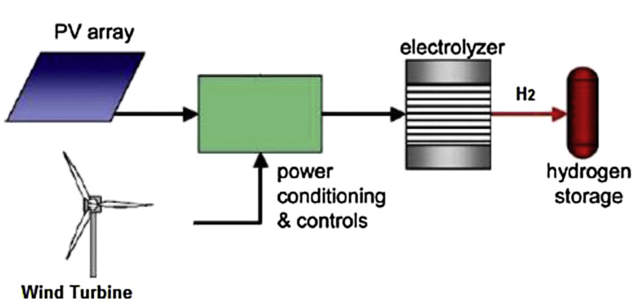

Fig. 6 – Schematic diagram of hydrogen production chain from wind and solar energies.

Estimation of hydrogen production from renewable resource

Once the potential for the annual mean of the available solar and wind electric energy is assessed using renewable resources databases within the specific location, the technical potential of the annual hydrogen production from these renewable resources can be estimated as follows [34]:

$$M_{H_2} = \frac{E_{H_2}}{HHV_{H_2}} = \frac{\eta_{Elec} E_{RES}}{HHV_{H_2}} \tag{7}$$

Where M_{H_2} [kg/km^2/year] is the annual hydrogen production, E_{H_2} [kWh/km^2/year] is the hydrogen energy produced, HHV_{H_2}[kWh/kg] is the hydrogen higher heating value (39.4 kW h/kg), η_{Elec} is the efficiency of the electrolysis system and E_{RES} [kWh/km^2/year] is the renewable power production.

An overview of the calculation steps is given in Fig. 7.

Solar hydrogen production analysis

Fig. 8 shows the map of hydrogen potential from solar energy using the considered mono-crystalline photovoltaic panels. For all the results that follow, the unit of hydrogen potential is tons of H_2/km^2/year.

Solar electricity and hydrogen production potential are directly proportional; when the region, which has the highest electricity production potential, has the more estimated hydrogen production. The quantity of hydrogen that can be produced from solar photovoltaic energy is more than 2.4×10^5 tons/km^2 per year in the country. As seen Fig. 8, it can

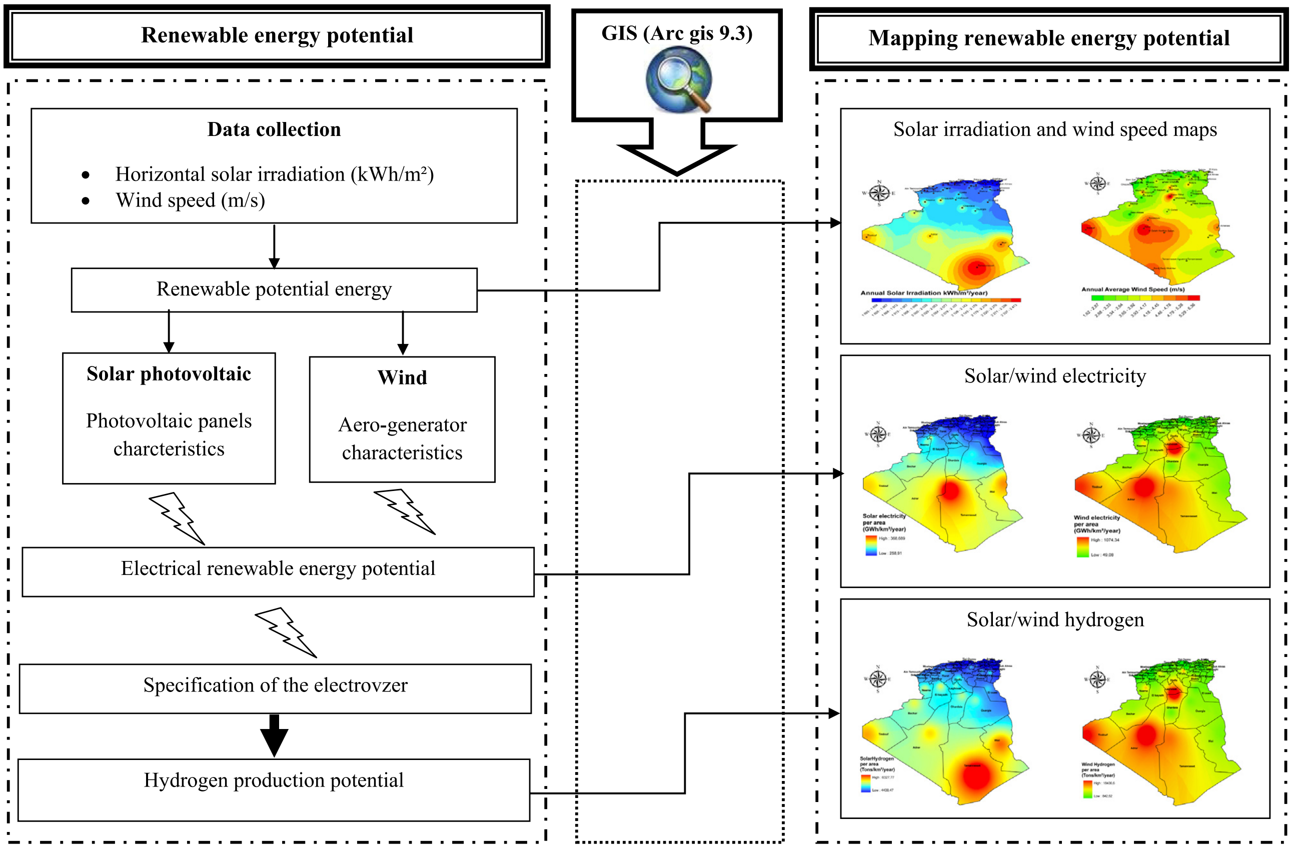

Fig. 7 – Flowchart representation for the evaluation of renewable hydrogen production potential in Algeria using Geographical Information System (GIS).

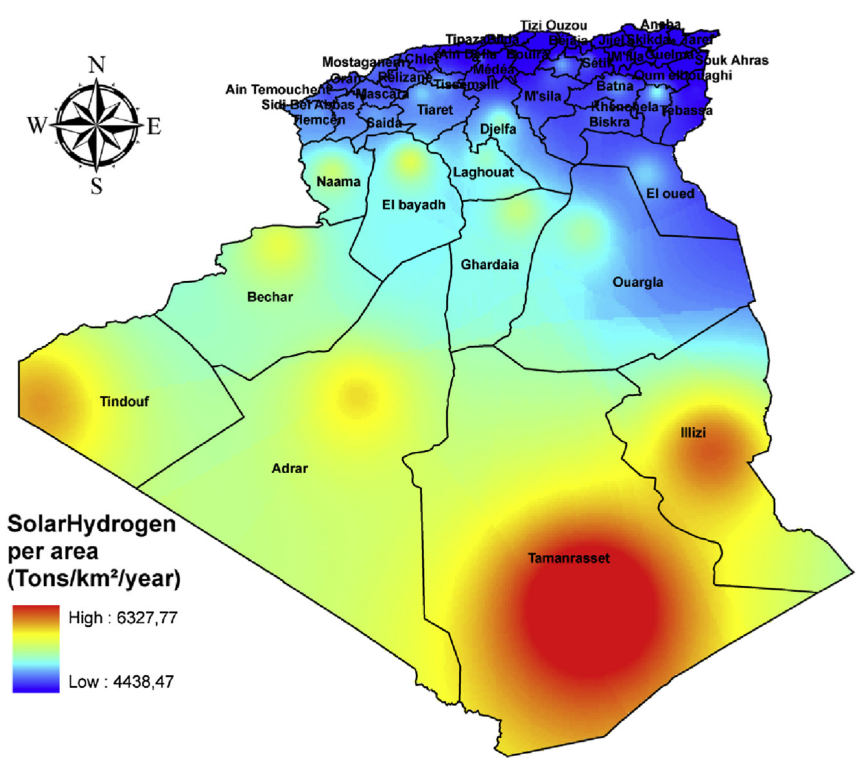

Fig. 8 – Hydrogen potential from solar energy.

observe that, the total annual solar hydrogen is ranged between 4437 and 6327 tons/km^2 yearly, which are reached respectively in El Taref (northeastern region) and Tamenrasset (southern region). In fact, the estimated solar hydrogen over the country does not present important differences between all regions. In addition, the highest potential for producing solar hydrogen in the whole territory is located in South of Algeria.

Wind hydrogen production analysis

Wind hydrogen is essentially the generation of hydrogen by electrolysis where in the electricity supplied is derived from wind turbines. Fig. 9 shows the map of annual potential for hydrogen production from wind energy, averaged over the area of each region. To calculate the wind energy produced by the selected turbine at a given site, the Weibull distribution corresponding to this site was integrated along with the capacity curve of this wind generator.

The hydrogen mass produced from wind energy shows a remarkable different behavior than the one observed for the solar and varies significantly by region. From the Fig. 9, we can see that Hassi R'mel (Laghouat), Adrar and Tindouf regions are highlighted, with an annual potential production exceeding 12×10^3 tons of wind hydrogen per square kilometer, where the maximum value is given in south at Hassi R'mel site with 18447.6 tons/km^2/year. On the other side, with an annual potential between 5×10^3 and 10^4 tons/km^2, we can fine Oran, Souk-Ahrass, Tindouf, Tiaret, Biskra, Djelfa, Naama and Tamenrasset regions. In Bordj-Bou-Arerij, Tizi-Ouzo, Tlemcen, and Mestaganem, we can find the lowest amount of hydrogen mass, which is about 800 tons/km^2/year.

Comparison between solar and wind hydrogen production potential in Algeria

As seen in the previous results, hydrogen production using renewable energies, is mainly related to the solar and wind energy potential which affects directly the electrical potential from each source, therefore the estimated hydrogen production and the renewable electrical potential are directly proportional. However, the distribution of hydrogen production from solar and wind behaves differently, and that is due to the varied nature of the source, and due to the geographic site specification, climatic conditions and technological limitations of each resource in the largely scattered surface of the Algerian territory. Fig. 10 shows the comparison of the estimated production potential from both resources for each region.

As seen in Fig. 10, solar based hydrogen production potential varies in a quite small interval from the highest estimated potential in Tamenrasset by 6328 tons/km^2 yearly to the lowest obtained potential in Al-Taref by 4437.14 tons/km^2 yearly comparing to the estimated wind based hydrogen production, which varies differently in a quite large interval, the highest estimated hydrogen production was obtained in Tamenrasset by 18447.6 tons/km^2 yearly to the lowest obtained value in Tizi-Ouzou 838.6 tons/km^2 yearly.

The sum of hydrogen production potential for wind and solar energies can indicate the optimal regions for projects of

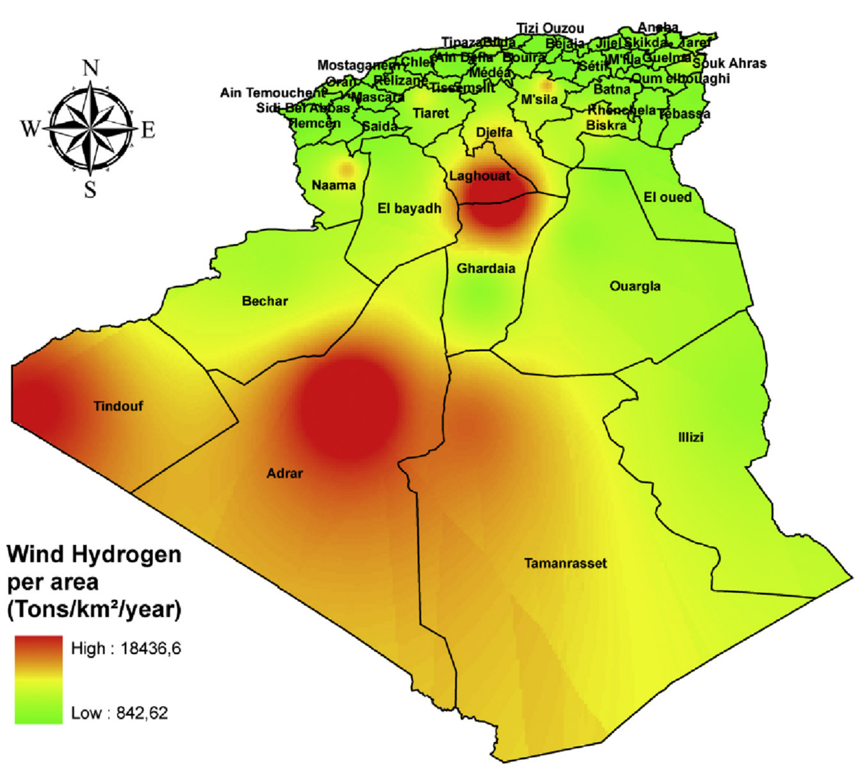

Fig. 9 – Hydrogen potential from wind energy.

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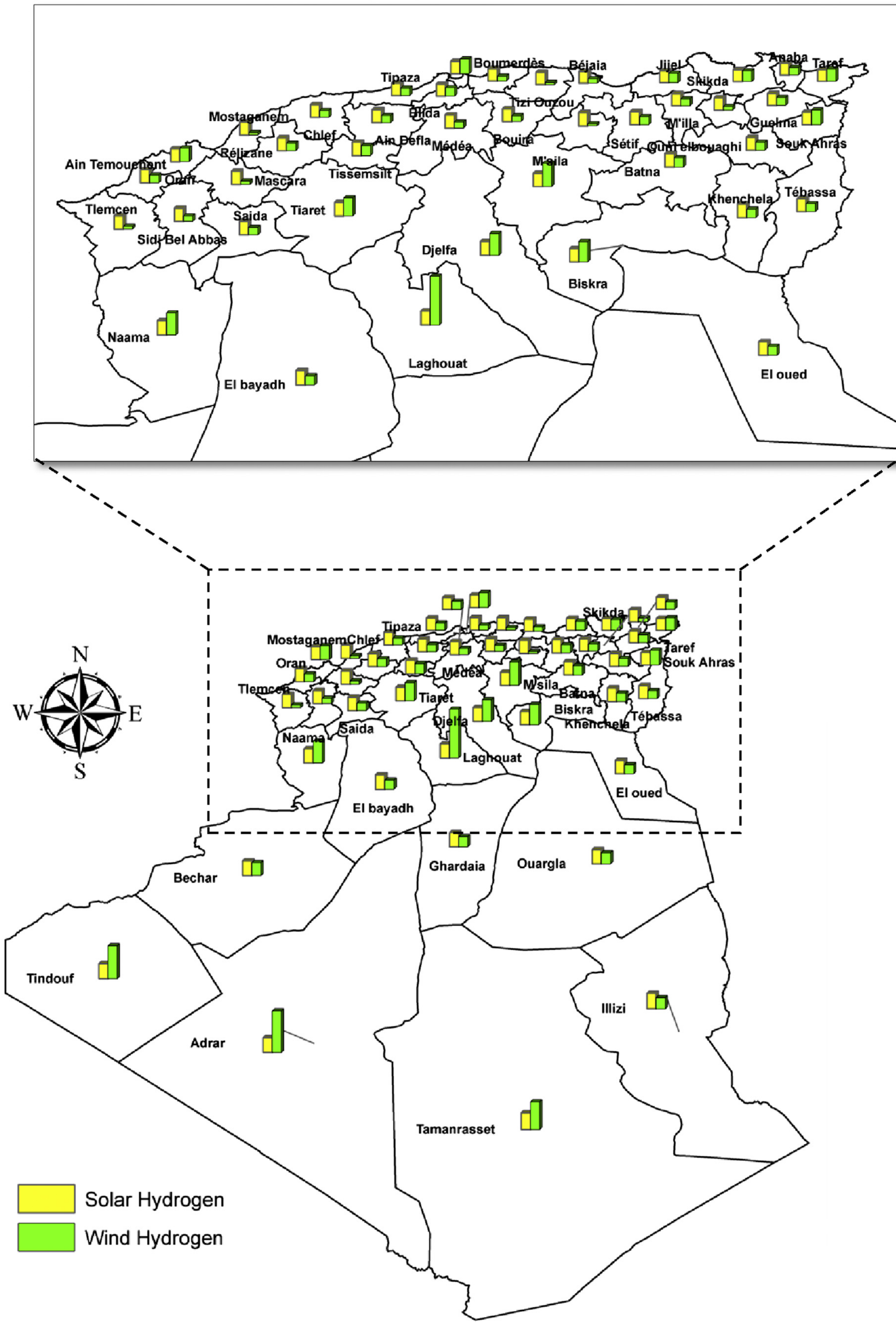

Fig. 10 – Comparison of solar and wind hydrogen production potential in Algeria.

hybrid solar–wind hydrogen production. The regions of Adrar and Laghouat can produce more than 2×10^4 tons/km^2 yearly. In addition, for a capacity production comprised between 2×10^4 tons/km^2/year and 1.3×10^4 tons/km^2/year we find the following regions: Tindouf with 1.8×10^4 tons/km^2/year, Tamenrasset with 1.68×10^4 tons/km^2/year, Djelfa, M'sila and Naama with 1.3×10^4 tons/km^2/year. Also, the regions that provide an annual production of 1×10^4 tons/km^2/year are: Biskra, Tiaret, Bechar, Algiers, Souk-Ahras, Oran and Illizi.

Based on the obtained results and for purposes of illustration, we classify the results into three categories. The first class comprises regions with the potential of producing hydrogen from wind power is higher than the production through the use of solar energy. These regions are concentrated in the Southern and Southwestern parts of Algeria; namely: Adrar, Laghat, Biskra, Tamanrasset, Tindouf, Djelfa, M'sila and Naama. The second category contains regions with the potential of producing hydrogen from solar energy is higher compared to the wind based hydrogen production. In this class we find many regions of the West (Chlef, Tlemcen, Saida, Sidi-Bel-Abbas, Mostaganem, Mascara and Ain-Tmouchent), coastline (Béjaia, Boumerdès, Tipaza), East (Oum-El-Bouagui, Tbessa, Sétif, Annaba, Constantine and Khenchla), and from the South only El Oued region. The latter group includes the rest of the region that has a balance and equality between the productive potentials of wind and solar hydrogen, like Ouargla, Algiers, Oran, Batna and others. In the southern part of the country the solar and wind energy are both convenient, however, in the northern side solar based hydrogen is more probable for a large scale hydrogen production exploitation.

Conclusion

This paper analyses the estimation of hydrogen production potential via water electrolysis with electricity produced from two renewable resources, namely solar and wind energy in Algeria, using meteorological data, satellite measurements and technical models. To this end, three modules are considered: the assessment of solar and wind potential, the estimation of electricity production, and the analysis of renewable based hydrogen production potential. The hydrogen potential is analyzed and assessed for comparison purposes. The following conclusions can be drawn:

- The available solar irradiation varies in a quite small interval from the highest irradiation in Tamenrasset equal to 2413 kWh/m^2/year to the lowest irradiation in Al-Taref of 1692 kWh/m^2 yearly. The wind speed varies differently in a quite large interval, the highest wind speed was obtained in Adrar (6.38 m/s) to the lowest obtained value in Tizi-Ouzou (1.6 m/s).
- From the recorded wind data, it seems that all southern regions as well as some southwestern regions are more promising than others for the exploitation of wind resources for energy and hydrogen production. In particular, two locations encompass a high wind energy potential, which correspond to Laghouat (exactly in Hassi R'mel region) and Adrar region with wind energy production values equal to 1074.88 and 915.09 GWh/km^2/year, respectively. Also, leads to a production of electrolytic hydrogen of 18447.6 tons/km^2/year and 15705.3 tons/km^2/year, respectively.
- In the solar energy case, the estimated solar energy and hydrogen do not present important differences between all regions of the territory. The total annual solar electricity potential is ranged between 368.7 and 258.5 GWh/km^2, which are reached respectively in Tamenrasset and El-Taref. The corresponding hydrogen production potential from solar photovoltaic panels equal to 6327.19 and 4437.14 tons/km^2/year, respectively.
- The results give a total annual production of 2.4×10^5 tons/km^2 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. It can be concluded that the Algerian Sahara is optimal for projects of large-scale solar and/or wind hydrogen production.

The estimated hydrogen potential can greatly enhance the quality of life in Algeria by creating jobs, developing technical skills, reduce the country's dependence on oil and gas, while meeting the obligations of reduced greenhouse effects and global warming. Also, in the upcoming years, the exploitation of these renewable energy potentials in a large-scale hydrogen production will make Algeria one of the biggest world suppliers of electricity as well as the revolutionary energy vector of hydrogen.

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