Sustainable Hydrogen Production in Yucatan

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ABSTRACT

More than 90 % of the hydrogen production in the world depends on carbon compounds, principally fossil fuels, and its use as energetic vector is only justified in some applications as fuel for spaceships or demonstrative buses or cars. The goal of this proposal is to compare different approaches for sustainable hydrogen production as a commercial activity in rural communities in Yucatan. The Yucatan peninsula is a particular region at the Southeast of Mexico, where a fragile environment is present in combination with poor rural Mayan communities. Moreover, energy supply in this region depends mainly on fossil fuels provided from other regions. However, in Yucatan, solar radiation and winds have an important potential application that has not been exploited yet. An application of these renewable energy sources could be hydrogen production as an economic activity promoting rural development of the region.

According with meteorological analysis, as well as with the consideration of energy requirements and efficiency of commercial electrolysis systems, an estimation of the hydrogen production is evaluated, considering both investment and maintenance costs. This estimation may be a reference in order to propose small industries for the production of hydrogen in specific rural communities in Yucatan. A transportation network organized by the regional government could be a solution to consume this hydrogen as fuel, although a number of other applications may be proposed depending on the regional energy requirements. Finally, the bioproduction of hydrogen is explored in order to compare it with the simple hydrolysis systems. Until the moment, as far as we can research, there are not commercial methods to produce biohydrogen and it is necessary to evaluate the capacity of bioprocesses to produce hydrogen.

1. Introduction

In Mexico, the Yucatan Peninsula includes three federal states: Campeche, Quintana Roo and Yucatán, which involve 7.1% of the national territory but only 3.7% of the total population (Table 1). In the national context, the three States represent in surface the 6.5% of the urban areas, the 5.2% of the agriculture regions and the 13.5% of the natural protected areas.

Table 1. Key information for the three Mexican states in the Yucatan Peninsula.[a]

State	Campeche	Quintana Roo	Yucatán	Peninsula
Surface (thousands km^2)	57.9	42.4	39.6	139.9
Population (million)	0.82	1.33	1.96	4.11
% Rural Population	25	12	16	17
% Indigenous Speaking Population	12	16	30	22
% National Gross Domestic Product	1.2	1.6	1.4	4.2
Urban areas surface (km^2)[b]	184.66	217.01	421.05	822.72
Agricultural surface (km^2)	2,341.65	1,238.15	7,844.78	11,424.58
Natural protected areas surface (km^2)[c]	17,544.12	12,500.97	4,451.30	34,496.39

[a] Values from the National Census 2010 [1], unless any other reference is given.

[b] Values for the year 2005 [1].

[c] Values for the year 2010 [2].

Being an important oil and natural gas producer in the last decades, Mexico has been energetically independent, with both the oil and the electrical sectors as Federal industries: Petróleos Mexicanos (PEMEX) and Comisión Federal de Electricidad (CFE), respectively. In the last years, the annual energy supply has reached more than 8 EJ in the country (around 75 GJ per capita). More than 90% of this energy is produced from fossil fuels and almost the half is used in transportation [3]. Table 2 includes a comparison of the general energy data in the Peninsula, in which electricity is produced exclusively from fossil fuels in 16 different plants, representing around 4 % of the total production and consumption in Mexico. Not only fragile ecosystems are detected in the region, there are also important touristic services, which generate important economic incomes. For these reasons, it is important to develop a systematic analysis to detect potential energy production from renewable sources in the zone. A special interest is in proposing sustainable processes, where not only economic but also environmental and social issues should be considered.

Table 2. Electrical services in the three states, compared with the national supply.

	Campeche	Quintana Roo	Yucatán	Peninsula	Mexico
Installed capacity (MW)[a]	449	285	1,532	2,266	51,172
Brut generation (TWh)[b]	2.0	Not available	8.7	-	241.5
Annual sells (TWh)[b]	1.1	3.6	2.8	7.5	186.6
% Population with electrical services[c]	95.8	94.5	96.6	95.7	96.2
Electrical supply (kWh per capita)[d]	1,331	2,734	1,454	1,843	1,661

[a] Values for March 2011 [4].

[b] Values for the year 2010 [3].

[c] Values form the 2010 National Census [1].

[d] Estimated values with the 2010 sells and the National Census population.

The general aim of this project is to develop an analysis of sustainable processes to use renewable sources of energy in the States of Campeche, Quintana Roo and Yucatan, Mexico. The natural resources to be considered are solar, wind and biomass, with interest to produce clean electricity and gaseous fuels (methane and hydrogen).

2. Methodology

Databases from both satellite and meteorological sources were used to analyze the solar and wind resources of the region. The National Renewable Energy Laboratory (NREL) has published an analysis of the solar potential in the region as a renewable source of energy [5]. The solar resource potential is shown in three different modes for Mexico, Central America and the Caribbean Islands: (i) for use with horizontal flat-plate collectors, (ii) for use with flat-plate collectors tilted at latitude, and (iii) for use with 2-axis tracking concentrating collectors. The data were developed from NREL's Climatological Solar Radiation Model, but the resolution is reduced to a geographical grid with cells of approximately 40 km by 40 km in size; the modeled values are accurate to approximately 10% of a true measured value within the grid cell. The NREL has published also an analysis of the wind potential in this specific region as a renewable source of energy and a database (provided by Anthony Lopez in the GIS group) is available for the offshore wind potential in Mexico.

The Cinvestav-Merida manages at the moment four meteorological stations in the state of Yucatan. The oldest is installed in the Merida campus, and three more are installed in the North cost: from east to west, they are in Telchac Puerto, Chelem and Sisal. The stations are installed on towers at 10 m height and automated records are periodically performed every 10 minutes; the corresponding databases were provided by David Valdés in the Department of Recursos del Mar.

The System Advisor Model (SAM), developed by the NREL [6] was used here to analyze two hypothetical medium-scale electrical plants: a wind farm in Sisal, where the best wind potential is found in the region, and a PV plant in Merida, where the maximal energy requirements are found. For every plant, a 500 kW installation was considered, which is the maximal capacity allowed by CFE-Mexico for commercial electricity production. Although most of the default values were used, different variations were tested for every plant, representing a number of scenarios.

3. Results and discussion

Table 3 resumes the solar potential for the Yucatan Peninsula from the NREL database with a satellite model; it is possible to see that tilted collectors represent the best way to use the solar radiation in the region. However, considering photovoltaic (PV) systems, there is only a small fraction of these solar resources that can be transformed to electricity. Following the methodology proposed by Denholm and Margolis [7], under Standard Test Conditions (1000 $W \cdot m^{-2}$ of solar irradiance at 25°C), a 13.5 % efficiency is considered for the PV modules (commercial systems range from 6 to 26 %). Moreover, when a minimal spacing is considered between arrays to allow maintenance, the total system power density (per unit of array area) is reduced from 135 to 65 $W \cdot m^{-2}$. Finally, the efficiency of the inverter to convert direct current (DC) generated by the PV modules to alternating current (AC) depends on many variables, a value of 70 % was considered in this work. An annual estimation of (92 ± 3) $GWh \cdot km^{-2}$ is obtained as a rough average in the region with tilted PV systems.

Table 3. Annual Solar Radiation in the Yucatan Peninsula.

	Radiation ($kWh \cdot m^{-2} \cdot day^{-1}$)		
Collectors	**General Range**	**More Frequent Range**	**Average[a]**
Horizontal	4.5-6.0	5.0-5.5	5.2 ± 0.2
Tilted	5.0-6.0	5.0-5.5	5.5 ± 0.2
2-Axes	3.5-6.0	4.5-5.0	5.0 ± 0.4

[a] Uncertainty is the standard deviation of the mean value.

If it is considered the electricity consumed in the region during 2009: 7,617.31 GWh, and using the estimated solar-to-electricity potential for the region, a surface of only (83 ± 3) km^2 is required to supply the electrical needs of the Yucatan Peninsula. If considering that the electrical consumption is about 10 % of the total primary energy supply, less than 900 km^2 of land surface would be needed to satisfy the energetic needs of the whole region with PV technologies. To compare, this surface represents roughly about the half of the urban area of Merida or the 0.6 % of the total surface in the Yucatan Peninsula.

The solar resources in the region could also be analyzed as a footprint, defined by Denholm and Margolis [7]. When the annual electrical demand of the region, 1,843 kWh per capita, is divided by the corresponding PV energy density, (92 ± 3) $kWhm^{-2}$, the solar electric footprint is only (20 ± 1) m^2 per capita. This means that if every inhabitant installs 20 m^2 of a PV system, the electrical demand should be satisfied for the region. This footprint can be diminished to around the half if the PV systems are installed in small arrays. The USA average is 181 m^2 per capita, ranging from 354 in the state of Wyoming to 89 in the state of California. At this point, it is natural to question why so a "small" system is not already installed. The answer is easy: there are a number of restrictions, including relatively high costs, intermittent output and land use. In the Unites States, by instance, scarcely 1% of the electricity supply is provided by PV systems.

Analyzing the wind resources in the Yucatan Peninsula, only a stretch line in the Caribbean coast (Riviera Maya) and a small tip at the Northwest of the Peninsula (Sisal), beside other smaller areas, show moderate to good potential use (Class 4). Nevertheless, the Riviera Maya beaches in Quintana Roo are reserved as environmental protected areas or touristic zones and a wind farm in this surface would be not appropriate. Considering the Sisal region in the state of Yucatan, an assessment of the annual wind energy density could be envisaged through a number of scenarios using a three-factor analysis, with minimal and maximal values for every factor: the capacity factor, the height of the wind turbines and the capacity density. Table 4 describes the eight proposed scenarios for 1.5 MW wind turbines with 77-m rotor diameter; note that for this turbine, the recommended capacity density is 5 $MWkm^{-2}$ [8]. In the USA, the most popular wind turbines in the last 5 years are in the size range from 1.01 to 1.5 MW, although the market for capacities larger than 1.5 MW has been increasing [9].

Table 4. Scenarios to determine the annual wind energy density in the Sisal region.

Scenario (Wind Class 4)	Capacity factor (%)	Height (m)	Capacity density ($MW·km^{-2}$)	Energy density[a] ($GW·km^{-2}·year^{-1}$)
1	30	50	2	7 – 8
2	30	50	10	33 – 41
3	30	100	2	9 – 11
4	30	100	10	45 – 55
5	50	50	2	11 – 14
6	50	50	10	54 – 68
7	50	100	2	15 – 18
8	50	100	10	75 – 92

[a] Ranges correspond to minimal and maximal power densities for wind Class 4.

Assuming the capacity factor of 33.8% suggested by Aabakken [10], the capacity density of 5 $MWkm^{-2}$ calculated by [8], and a height of 80 m that is the average installation in for wind turbines in the USA [9], the annual energy density for the Sisal region is (25.3 ± 2.3) $GW\cdot km^{-2}\cdot year^{-1}$, where the mean and the uncertainty values correspond to the Class 4 wind power densities range. The annual electrical needs of the state of Yucatan, 2,939.55 GWh, would require a wind farm of (116 ± 12) km^2. If compared with PV systems, wind turbines require more land; however, wind plants could combine uses with other activities as agriculture [8].

Since Denmark's first project in 1991, Europe has held the lead in offshore wind, but the installed capacity and the technologies are still limited [11]. However, interest is being spread to the international community and the market is continuing to expand. Analyzing the potential of wind resources at 90 m over the sea level, maximal wind speeds (8 to 9 $m\cdot s^{-1}$) are observed in the Caribbean Sea, but an enormous shipment density can be detected also in this marine region. However, most of the national Gulf of Mexico presents an attractive wind potential (7 to 8 $m\cdot s^{-1}$) without high density of shipment routes. Moreover, around the Yucatan Peninsula, the oceanic waters are shallow, characterized by short bathymetric distances, diminishing technical barriers to install offshore wind farms. Nevertheless, any offshore wind development have to be evaluated in the context of hurricanes that frequent the region, and an risk factor must be considered in the structural design of any turbines that are put in place.

Table 5 condensates the average values for the meteorological data in four stations in the Yucatan state. In general, the average values are in good agreement with those from the NREL database. These average values are also consistent with those reported by the NASA-USA [12] from satellite measurements and correlation models in a low-resolution grid, but with 22-year averages for temperature and solar radiation values, and a 10-year average for wind speed values. The NASA information complements those from the meteorological stations to estimate monthly mean values for diffuse horizontal and direct normal radiations, as well as atmospheric pressure and albedo values. Annual files with 8,760 hourly variations of the solar and wind resources can be constructed for every meteorological station in order to analyze with more detail their potential for electricity production. These files are used to analyze the performance and economics of renewable energy technologies.

Table 5. Average values from four meteorological stations owned by Cinvestav-Merida in the state of Yucatan.

	Mérida	**Telchac**	**Chelem**	**Sisal**
Temperature (^oC)	26.4	25.4	25.2	24.2
Global horizontal radiation ($kW\cdot h^{-1}\cdot day^{-1}$)	5.30	5.64	5.82	5.31
Wind speed ($m\cdot s^{-1}$)	2.64	4.98	4.59	5.06

Tables 6 and 7 show the main results for two hypothetical 500-kW plants with a 30-year lifetime, using the System Advisor Model (SAM). The economic analysis has to be improved for the conditions in Mexico, but give an idea of the cost differences among proposed scenarios. Table 6 represents different scenarios for the hypothetical wind plant in Sisal. Scenarios 3 to 6 consider four different turbine models and sizes: Endurance Wind E-3120 (E), with 50 kW of capacity and 19.2 m of rotor diameter; Northern Power Northwind 100 (N), with 100 kW of capacity and 21 m of rotor diameter; AOC 15-50 Wind Turbine (A), with 63 kW of capacity and 15 m of rotor diameter; and WTIC Jacobs 31-20 (W), with 20 kW of capacity and 9.4 m of rotor diameter. All of these turbines are supposed to be installed at 80-m height. The most attractive model is that of scenario 3 and it is used to compare with a 30 m hub-height installation (scenario 1), a plant with just 100 kW of installed capacity (scenario 2), and the same plant in scenario 3 but installed in Mérida (scenario 7).

Table 6. Wind farm at Sisal considering different scenarios.

Scenario	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Turbine model	E	E	E	N	A	W	E
Hub height (m)	30	80	80	80	80	80	80
Total surface (m^2)[a]	9,600	1,920	9,600	5,250	6,000	11,750	9,600
Total installation cost (M$US)[b]	2.540	0.556	2.540	1.996	2.334	4.173	2.540
Produced energy (GWh·year^{-1})	1.530	0.388	1.940	1.298	1.244	1.205	0.548
Pay back period (years)	12.3	11.2	9.0	11.4	14.8	> 30	> 30
LCOE nominal (¢US/kWh)[c]	8.69	6.87	6.85	8.21	9.88	17.65	24.24
LCOE real (¢US/kWh)[c]	6.67	5.23	5.26	6.30	7.58	13.54	18.60

[a] Estimated from the recommendation 10D x 5D by Denholm [8].

[b] Land costs are not included; differences in hub-height installation costs are not considered.

[c] Levelized costs of electrical energy, accounting the effect of inflation (real) or excluding it (nominal).

From these results, it is possible to see that the type of installed turbines is determinant for the performance of the wind plant, and not just the costs but also the technical characteristics are important. The hub height is also important for the amount of transformed energy, but the installation costs should be different and the model must be adjusted in this case. It is interesting, however, that no big economic differences can be found when the plant is reduced five times in installed capacity; this could motivate different size projects, depending on financial and land availabilities. Nevertheless, the local wind resources are extremely important and it is shown here that Mérida is not a good place to install a wind plant.

Table 7 resumes a series of scenarios for the hypothetical PV plant installed in Merida. A big variety of commercial systems are available in the SAM database; but the PVWatts System Model was used instead to simplify the comparisons. Scenario 1 is for a plant with an installation of just 100 kW, while the other scenarios are for a 500-kW plant. Scenarios 2 to 4 give the differences when the type of installed array is changed from tilted to tilted with one tracking axis and to 2-axis tracking. Scenario 5 considers a lower DC-AC conversion than the other systems. Finally, scenario 6 is for the same system in scenario 3 but installed in Sisal.

Table 7. PV plant in Mérida considering different scenarios.

Scenario	**1**	**2**	**3**	**4**	**5**	**6**
AC-DC conversion (%)	77	77	77	77	70	77
Array	1-axis	Tilted	1-axis	2-axis	1-axis	1-axis
Total surface (m^2)[a]	2,083	7,692	10,417	25,000	10,417	10,417
Total installation cost (M$US)[b]	0.450	2.249	2.249	2.249	2.235	2.249
Produced energy (GWh $year^{-1}$)	0.172	0.705	0.860	0.901	0.781	1.011
Pay back period (years)	24.5	> 30	24.5	22.7	28.4	19.0
LCOE nominal (¢US/kWh)[c]	13.80	14.70	13.80	13.17	15.12	11.74
LCOE real (¢US/kWh)[c]	10.59	11.28	10.59	10.11	11.60	9.01

[a] Estimations from PV array power density values given by Denholm and Margolis (2008).

[b] Land costs are not included; differences in array-installation costs are not considered.

[c] Levelized costs of electrical energy, accounting the effect of inflation (real) or excluding it (nominal).

The results let see again that the performance and costs of a system are not important when a 100 kW or a 500 kW plants are installed. However, the pay back period and the LCOE values should be reviewed to verify if there is not an error in the calculations. The performance of the systems is improved if one or two tracking axis arrays are installed, reducing the cost of the produced electricity, but again the model should be reviewed in the installation costs. Moreover, the land-use in the 2-axis arrays diminishes its interest if the footprint is considered. Finally, when comparing the results for a PV plant in Merida and in Sisal, it is important to remark the importance of the location of the plant, accordingly with the available regional resources but also with the needs of energy. Not only the electricity production costs should be considered but also the lost of transmission when the energy is not consumed at the place of production. In addition, the retail prices should be considered when connected to the electricity grid in commercial systems.

When comparing the scenario 3 in table 6 for a wind farm, with the scenario 6 in the table 7 for a PV plant, both installations in Sisal, the land requirements and installation costs are similar. However, the wind system gives an economical advantage over the PV system in the levelized costs of electrical energy. Nevertheless, the use of the land should be reviewed with more detail: the wind plant allows another open-air activities among the installed turbines, including agronomical production. On the other hand, the PV installations are also attractive because of the potential shadow they can offer: when direct radiation is avoided in some systems, an important amount of energy consumption is saved from refrigeration systems. More scenarios can be reviewed considering specific interests of the Yucatan state government, investors and municipalities. A review of the local costs should be also done to consider them in the economical analysis, including retail prices for the regional grid pricing structure. In addition, some social and environmental implications must be added to the balance in order to have a full view of the advantages of investing in renewable energies.

The potential for hydrogen production from renewable resources in the United States have been already studied [12-13]. The typical energy requirements for electrolyzers range from 53 to 70 kWh per kilogram of hydrogen, with an average of 58.8 kWh kg^{-1}. Saur and Ramsden [14] have used an efficiency value of 50 $kWh \cdot kg^{-1}$ and an operating capacity factor of 98% for wind electrolysis plants. In addition to the energy requirements for water electrolysis, some more energy is required if hydrogen is used for refueling stations in transportation systems. Around 72 kWh per kilogram of produced hydrogen is considered for a small filling station, with approximately more 3 $kWh \cdot kg^{-1}$ needed for compression, storage and dispensing [13]. These values were considered to estimate the hydrogen production capacity of the electrical plants proposed just before. Table 8 presents an estimation of hydrogen produced with electrical energy from wind farms and PV plants in Mérida, Telchac, Chelem and Sisal. If a 12-passenger hydrogen-powered shuttle bus is used, with an efficiency of about 9.3 km per kilogram of hydrogen, it is possible to calculate the distance that could be driven every day from the hydrogen fuel station.

Table 8. Estimation of hydrogen production from PV or wind plants in Yucatan.

Plant		Transformed energy ($GWh\ year^{-1}$)	H_2 production ($kg\ year^{-1}$)	H_2 production ($kg\ day^{-1}$)	Driven distance ($km\ day^{-1}$)
Wind	Sisal	1.940	25,867	70.9	659.1
Wind	Telchac	1.882	25,093	68.7	639.4
Wind	Chelem	1.574	20,987	57.5	534.7
PV	Chelem	1.016	13,547	37.1	345.2
PV	Sisal	1.011	13,480	36.9	343.5
PV	Telchac	0.988	13,173	36.1	335.6
PV	Merida	0.860	11,467	31.4	292.2

As can be observed, the hydrogen plants using wind technologies have better yields than using PV systems. In addition, the communities along the coast of Yucatan show better results than Mérida. A more detailed analysis must be done in order to consider the costs involved in these systems, the requirements of water for electrolysis, and the social and environmental implications to establish a network of public transportation fueled by hydrogen in the region.

Finally, table 9 gives an estimation of a microalgae (*Chlamydomonas reinhardtii*) plants for hydrogen production in Mérida, with an average of the hydrogen production in the PV and wind plants analyzed before. It is interesting to see the potential of hydrogen production considering the land required in every plant. Although wind farms require more extensions of land, the net production of hydrogen is twice that of the PV plant and 2.5 times that of the microalgae plant. It has been remarked before that PV plants are more expensive than wind farms. Therefore, wind farms are more convenient to install than PV systems. For the microalgae plant, it is necessary to evaluate the required costs of installation and operation, since the hydrogen production is not so far away from that of wind systems. Therefore, additional research and technological development is expected for the algae production in order to have an alternative renewable system to the wind and PV systems in the region.

Table 9. Hydrogen production plants in Mérida.

Plant	**Annual hydrogen production ($kg \cdot m^{-2} \cdot year^{-1}$)**
Wind-Hydrogen	2.50
PV-Hydrogen	1.24
Microalgae-PV-Hydrogen	0.96

4. Conclusions

According with satellite databases, solar resources are an interesting possibility for the Yucatan Peninsula to produce energy. However, from meteorological measurements, wind resources are also important and even more attractive than PV systems to produce hydrogen as an energy vector. A system of wind-hydrogen plants along the Yucatan coast is proposed here as an alternative economical activity to fuel a public transportation system.

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