

Environmental impact associated with the substitution of internal combustion vehicles by fuel cell vehicles refueled with hydrogen generated by electrolysis using the power grid. An estimation focused on the Autonomous Region of Murcia (Spain)



J.J. López Cascales^{*}, M.C. Juan-Segovia, J. Ibáñez Molina, J. Sánchez Vera, P.M. Vivo Vivo

Universidad Politécnica de Cartagena, Escuela Técnica Superior de Ingeniería Industrial (ETSII), Grupo de Bioinformática y Macromoléculas (BioMac), Aulario II, Campus de Alfonso XIII, 30203 Cartagena, Murcia, Spain

ARTICLE INFO

Article history:

Received 8 April 2014

Accepted 25 November 2014

Available online

Keywords:

Fuel cell vehicles

Substitution ratio

Pollution

Electrolysis

Electric vehicles

Electrical power grid

ABSTRACT

This article explores the possibilities of substituting internal combustion vehicles (ICV) by fuel cell vehicles (FCV) refueled with hydrogen generated by electrolysis during the hours of low demand in the electrical grid, having been estimated that this substitution ratio would be below 25% of the total number of vehicles existing today, against the 100% in the case of using electric vehicles. Furthermore, a network of 322 hydrogen stations would be necessary for refueling the maximum number of fuel cell vehicles, given the actual limitations of the electrical grid for hydrogen generation. Thus, considering that hydrogen used for refueling would be generated by electrolysis using the electrical grid, fuel cell vehicles would only be a 4% less polluting than an internal combustion vehicle. However, if we could achieve a substitution ratio of 25% of the total ICV by FCV, the Autonomous Region of Murcia could avoid the emission of up to 24,500 metric Tons of CO₂ to the atmosphere every year. This value contrasts with the 2.2 millions of metric tons of CO₂ that could be avoided using electric vehicles.

© 2014 Elsevier Ltd. All rights reserved.

1. Introduction

Due to the increase in energy demand in most of developed countries during the last decades, a great number of public institutions and researching groups are actively seeking new energy resources much more efficient and less pollutant than the existing today. In this sense, the use of hydrogen for certain applications (from mobile to stationary power stations) has been proposed as a reasonable solution [1–3]. This recent movement proposes the use of hydrogen as a friendly fuel, mainly due to the following major reasons:

1. Hydrogen can be considered as an environmentally benign fuel, with zero emissions, if hydrogen used in fuel cells is generated by electrolysis using renewable energies [2]. However, on the opposite face of the coin, in spite of being the hydrogen the most abundant element in the nature (in mass), hydrogen is always

found forming compounds due to its great chemical reactivity. In this context, one of the major challenges that we must face for introducing the hydrogen in our society, is the developing of new methodologies for producing hydrogen in a more efficient manner.

Finally, we must remark that the statement of *the electrical current produced in a fuel cell is a friendly technology with the environment* only can be sustained after the evaluation of the whole process of hydrogen production.

2. In a great number of countries, the use of hydrogen could reduce their dependency on fossil fuels, and as a consequence, it would tend to alleviate the consequences of the periodical crisis in very localized areas of crude oil production [1]. However, nowadays almost 94% of the total hydrogen consumed around the world is generated from natural gas, and hence, a certain level of dependency on fossil fuels remains [1,2].

In this context, Spain imports huge quantities of natural gas and crude oil from other countries [4], showing a strong

^{*} Corresponding author. Tel.: +34 968325567; fax: +34 968325931.
E-mail address: javier.lopez@upct.es (J.J. López Cascales).

dependency on fossil fuels. Thus, the development of renewable energies is of crucial importance if Spain pretends to reduce such dependence. This fact explain why Spain has granted a great number of research projects and has also participated in many projects coordinated by the European Union during recent decades, for example the CUTE project (<http://www.global-hydrogen-bus-platform.com>) [1] or the Hychain project (<http://www.hychain.org>), in which hydrogen features strongly. Indeed, hydrogen is considered as an appropriate solution for overcoming the dependence on fossil fuels, once advances in fuel cell technology allows its use in vehicles with similar performances as new internal combustion vehicles.

However, one aspect that needs to be overcome before Fuel Cell Vehicles (FCV) can fully play an important role in our society, deals with the development of proper infrastructure networks for refueling these FCV [5–7]. Therefore, if we would like to extend the use of FCVs in our community, authorities and car manufacturers should provide potential drivers, of the same autonomy and refueling possibilities than the existing today, so that this new technology would become attractive for potential drivers. This reality will be achieved only after a mutual collaboration between public agencies (that should support the implantation of a network of hydrogen stations), and from private companies (that should obtain a business return from their investment).

In this respect, the aim of this work is the study of the capacity of the Autonomous Region of Murcia (located at the south-east of Spain, Fig. 1) to substitute conventional vehicles by FCVs. In this context, to ensure the complete success of such a process, the number of hydrogen stations required for refueling the maximum number of FCVs will be estimated, considering that the hydrogen would be generated in-situ at each hydrogen station using the electrical power grid. In addition, the environmental impact associated with the replacing of ICV (Internal Combustion Vehicles) by FCV will be estimated as well.

Although electrolysis is not the cheapest method for obtaining hydrogen compared with reforming of natural gas [1,2], this is a very mature technology employed in its production. The decision of

choosing the electrolysis as method for hydrogen generation is justified on the basis of the following premises:

1. As it was mentioned above, Spain imports great quantities of crude oil and natural gas [4]. In this regard, considering that Spain has increased the production of electrical current from renewable resources (for example, solar photovoltaic and thermoelectric) during the last years [8], some of this electrical current could be devoted to hydrogen generation.
2. Any increase in renewable energy power (by setting up new power plants) would immediately be translated into a diminution in the CO₂ emissions associated with the hydrogen generation, once the FCVs would be powered with hydrogen generated by electrolysis [4], which would allow Spain to converge toward the level of CO₂ emissions signed in several international agreements.
3. Because hydrogen is a very light gas (even in its liquid phase with a density of 70.9 kg/m³ at –253 °C [2]), the pumping of this gas through long pipelines (from central production plants) and its transporting by truck as compressed gas or as a cryogenic liquid, requires much higher costs than its production in situ [9].
4. If the production of hydrogen takes place in situ, the capacity of production could be increased by setting up local renewable power plants to supplement the capacity of the electrical power grid.

Bearing in mind all the said above, in this work we will calculate the substitution ratio of Internal Combustion Vehicles (ICV) by Fuel Cell Vehicles (FCV) on the basis of the available capacity of the electrical power grid existing in Murcia, and it's environmental impact associated with the reduction of CO₂ emissions.

2. Methodology

The results of this work are based on the public information provided by the Spanish National Grid (Red Eléctrica Española [10],

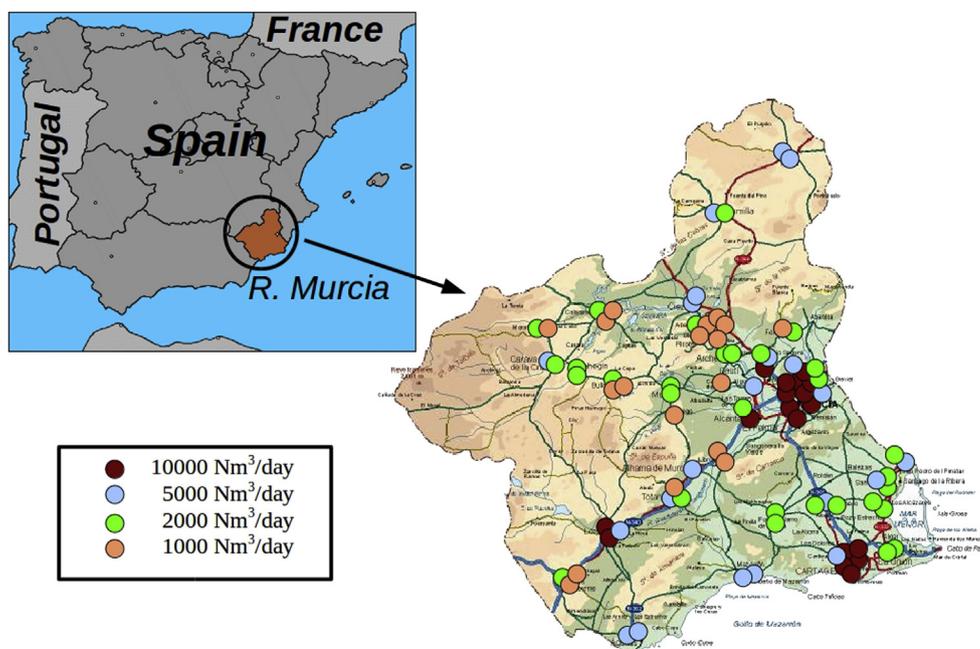


Fig. 1. Hydrogen station distribution in the Autonomous Region of Murcia. In this figure, we also marked the size of the different hydrogen stations.

a state-owned company which tracks the national power generation every 10 min) and from other official agencies.

2.1. Assignment of electrical power to the Autonomous Region of Murcia

The estimation of the electrical power in the Autonomous Region of Murcia that could be devoted to the hydrogen production, presents serious complications once the electrical grid interconnects the generation and demand of electrical power between the different autonomies (or regions) that conform the state. Thus, in a first instance, an evaluation of the global electrical power available in Spain is required, for in a second step, to assign part of this capability to Murcia under a criterion of population such as this will be argued below.

Furthermore, with the goal of avoiding an overcharge in the power grid due to a hypothetical excess of power demand devoted to hydrogen production, the available electrical power for hydrogen production will correspond to the hours of low electric demand, called *off-peak hours*, typically from 10:00 pm to 10:00 am, seven days per week. Hence, in this context, it will be considered that during these hours of low demand, the excess of energy will be devoted to hydrogen production, with the additional advantage that during these hours, the hydrogen stations could replenish their stocks that later will be used during the hours of a working day.

In this regard, the available electrical current that could be devoted to hydrogen generation is a key aspect of this study. In a first approximation, Fig. 2 shows the power demand corresponding to two days of two different weeks, of two different seasons as well: from the 16th to 22nd of July and from 17th to 23rd of December of

2012 (information obtained from the Spanish National Power Grid, Red Eléctrica Española [10]). By numerical integration of the area marked in Fig. 2 during the *off-peak hours*, average values of 182 ± 21 and 180 ± 20 GWh were estimated for the above mentioned weeks. Hence, on average, around 181 GWh are available per day for hydrogen production in Spain, during the hours of low electrical demand.

The electrical power in Spain is generated from different resources, such as follows: coal 15.9%, nuclear 22.10%, hydroelectric 10.56%, wind 11.09%, combined cycle 23.43%, others special regimes 16.41% and exchanges 0.5% (information provided by the website of the Red Eléctrica Española [10]). Obviously, in the process of assigning electrical power to hydrogen production during the *off-peak hours*, we could wrongly assume that photovoltaic energy is generated during some hours in which sunlight is not present. However, this gross approximation will not affect appreciably our results, since photovoltaic energy represents less than 3% of the total energy generated in Spain [11].

Thus, and considering that the population in Murcia is roughly a 3.4% of the total Spanish population [12], it was finally assigned an available electrical power to Murcia of roughly 6.2 GWh per day, once the ratio between people living in rural and urban areas, and the concentration of heavy industries in Murcia, approaches very much to the average value in Spain.

2.2. Estimation of the capacity of hydrogen generation

To estimate the capacity of hydrogen generation during the *off-peak hours*, in a first instance, we should design a hydrogen station model to which refers all our calculations. On the basis that it will be assumed that all the hydrogen is produced by electrolysis, in this section all the parts that constitute our model of hydrogen station will be defined previously to estimate the capability of hydrogen generation. In this respect, the technical information was taken directly from the technical data sheets of the different parts that conform the hydrogen station. Thus, Table 1 shows the electrical power required by the different equipments [6] that constitute our hydrogen station model: electrolyzer (NITIDOR [13]), purifier (IDROENERGY [14]) and compressor (PdC Machines [15]). In addition, with the aim of being realistic in our estimations, a certain amount of electrical power was included to consider the power used by the facility itself, such as lamps, air-conditioning and so on. Thus, Table 1 summarizes the energy used by the different parts that conform the hydrogen station referenced to Nm³ of hydrogen produced.

From Table 1, 5.7 kWh were estimated for every Nm³ of hydrogen produced. On the basis of all of these considerations, and bearing in mind (such as it was determined in Section 2.1) that the total electrical power available for hydrogen generation is of 6.2 GWh during the *off-peak hours* in Murcia, and considering that 5.7 kWh are required for every Nm³ of hydrogen produced, this

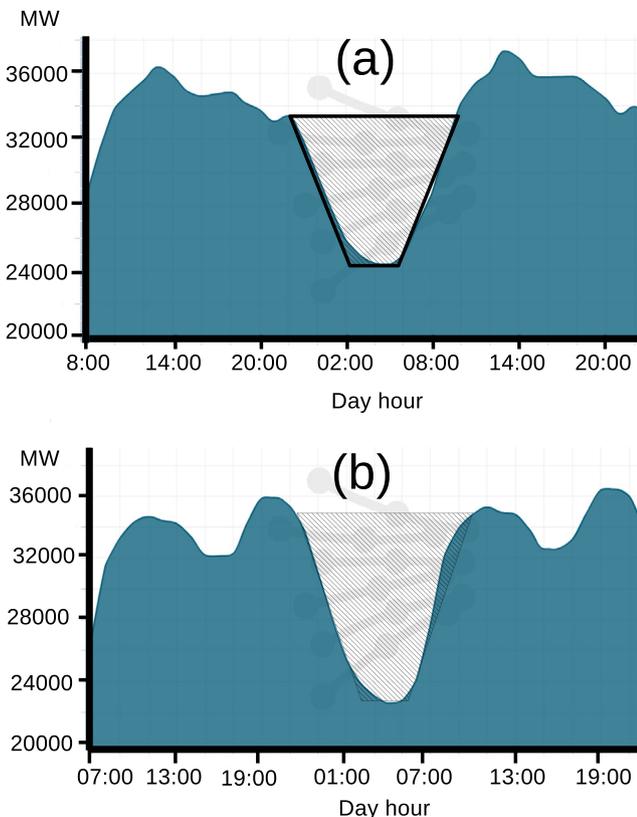


Fig. 2. Demand of power on July 18th (a) and December 18th (b) of 2012. Source, Red Eléctrica Española [10].

Table 1

Power energy used by the different components of a our model of hydrogen station: Alkaline Electrolyzer (NITIDOR [13]), Purifier (IDROENERGY [14]) and Compressor (PdC Machines [15]). The quantities assigned to the auxiliar device corresponds to the own consume during the hydrogen production.

	kW	Nm ³ /h	kWh/Nm ³
Alkaline Electrolyzer (NITIDOR)	500	100	5
Purifier (IDROENERGY)	0.5	15	0.033
Compressor (PdC Machines)	22.5	46.00	0.489
Auxiliar-devices (water treatment, ...)			0.18
Total:			5.7

means that a total of 1,070,424 Nm³ of hydrogen could be produced in Murcia every day without generating an overload in the electrical power grid.

3. Results and discussion

3.1. Fuel cell vehicle substitution ratio

A key aspect that must be evaluated is related with the estimation of the number of ICVs that can be substituted by FCVs, on the basis of the hydrogen availability. Thus, first of all, the number of vehicles that can be refueled using the hydrogen produced by electrolysis during the *off-peak hours* should be estimated.

For this, the technical information found in the technical data sheet of a Honda FCX Clarity [16] will be used. This car is a prototype of FCV already on the market, whose specifications are quite similar to those of a FCV Mercedes Clase B [17]. In this context, it will be assumed that the technical specifications provided by the manufacturer are true without further discussion from our side. In the Honda FCX, the hydrogen was stored as gas at high pressure because this provides better fuel economy, reduces the greenhouse gas emissions and is less complex than other technologies [18,19].

In this regard, Table 2 shows the main technical specifications of the Honda CFX Clarity that are relevant for our study. From information provided by the European Commission [4], a car is used to cover less than 50 km/day on average. Thus, considering that 6.4 Nm³ of hydrogen are needed to cover 50 km (Table 2), and that, the capacity for hydrogen generation in Murcia is of 1,070,424 Nm³ per day (such as we estimated above), that means that only 167,253 vehicles could be refueled with hydrogen every day. Hence, considering that the total number of vehicles in Murcia was 690,188 vehicles in 2011 [20], that means that only 24.2% of the vehicles could be substituted by FCV.

3.2. Hydrogen station network in the Autonomous Region of Murcia

The success of hydrogen penetration into our society will depend on providing to the FCVs of similar facilities to the existing today for the internal combustion vehicles (ICV) [21]. To success in this challenge, vehicles should be refueled everywhere, independently of the city or town in which drivers would reside or work.

With the aim of providing a first approximation to the number of hydrogen stations that would be necessary for refueling the FCVs in an efficient manner, the following considerations should be taken into account:

1. In broad lines, the total capacity of hydrogen generation in each town should be proportional to its population, although this assumption is not completely reliable because in rural areas, the number of vehicles is higher than in urban areas [12] (due to the fact that in general, these are isolated communities with lower ratios of public services than in urban environments, as for example, public transport among others).

Table 2

Car specifications used as model in our study corresponding to a Honda FCX clarity [16].

Power	100 kW
Fuel tank	171 L
Hydrogen pressure	350 bars
Fuel capacity (350 bars)	3.92 kg
Range	380 km
Consumption every 380 km	4 kg
kg of H ₂ per km	0.0105 kg/km
Consumption per km	0.128 Nm ³

2. Two hydrogen stations should not be separated more than 50 km to ensure that drivers are able to refuel their cars everywhere, once that it was considered as the mean distance that a driver covers every day [4].

3.2.1. Dispensing capacity in a hydrogen station

For our analysis, some additional considerations must be kept in mind, such as the refueling capacity of a hydrogen station. In this context, it will be considered that the distance covered per day in a FCV is of 50 km on average, and that the autonomy of a FCV is only of 250 km, instead of the 380 km mentioned on Table 2 for the Honda CFX Clarity. In addition, it will also be assumed that after each refueling maneuver, the vehicles will recover their complete autonomy of 250 km. Thus and based on the results of Table 2, in each refueling process 32 Nm³ of hydrogen will be used.

In this setting, and considering that a commercial dispenser for refueling FCVs, for example, the model TK16 H₂ [22] supplies between 100 and 120 g of hydrogen per second, and that the required time for refueling 4.5 kg of hydrogen (to reach a final pressure of 350 bars) is on average around 6 min (information obtained from the European HyChain project developed in Soria, Spain, <http://www.hychain.org/newhychain/index.jsp>), 8.95 Nm³ of hydrogen will be refueled per minute. Additionally, our calculations should also include a *dead time* of roughly 3 min between two consecutive refueling maneuvers, time that includes all the mechanical operations of removing and replacing the dispenser from the vehicle, together with the time for paying the bill. Table 3 depicts the time required for refilling a hydrogen tank.

Thus, considering that a dispenser is not in use continuously, that it works at roughly 25% of its maximum capacity and that a hydrogen station is open 16 h/day (assuming two working shifts per day of 8 h each), our dispenser shows a capacity of refueling of roughly 1168 Nm³/day, as specified in Table 4. Obviously, in these calculations it was considered that the demand is regular. However the fact is that some hours of high demand exist (rush hours) and others in which the demand is very poor (for example, during the weekend).

3.2.2. Hydrogen station network

As mentioned above, the capacity of hydrogen generation in the different cities/towns of Murcia should be associated with their population, so that all the FCVs should be able to be refueled using a Geographic Information System (GIS), as it has been proposed in other studies [23,24]. Thus, our next step will be to assign a quota of

Table 3

Required time for refueling to complete charge a vehicle with a range of 250 km. In this regard, a dead time of 3 min was taken into account as the time required to carry out the maneuvers related with the refueling in a gas station, which includes the removing and replacing the hose and payment.

Autonomy km	Consumption Nm ³	Refueling Nm ³ /min	Refueling min	Dead time min	Total time min
250	32	8.95	3.6	3.0	6.6

Table 4

Realistic capacity of a refueling dispenser in a hydrogen station, considering that this facility is open 16 h/day, and that the net use of each refueling dispenser is 25%.

Refueling h/day	Time in use %	Net time min	Refueling Nm ³ /day
16	25	240	1168

Table 5

Capacity of hydrogen generation assigned to each town is proportional to its number of inhabitants.

Town	Population	%	Nm ³ /day
Murcia	441,416	30.34	323,160
Cartagena	213,763	14.69	156,496
Lorca	92,699	6.37	67,865
Molina de Segura	65,796	4.52	48,169
Alcantarilla	41,378	2.84	30,293
Mazarrón	35,530	2.44	26,011
Cieza	35,383	2.42	25,904
Yecla	34,945	2.39	25,583
Águilas	34,945	2.39	25,583
Torre Pacheco	32,459	2.22	23,763
San Javier	31,874	2.18	23,335
Totana	29,389	2.01	21,516
Caravaca	26,465	1.81	19,375
Jumilla	26,026	1.78	19,054
San Pedro del Pinatar	23,833	1.63	17,448
Las Torres de Cotillas	21,347	1.46	15,628
Alhama	20,324	1.39	14,879
La Unión	18,423	1.26	13,487
Archena	18,130	1.24	13,273
Mula	17,107	1.17	12,524
Cehejín	16,230	1.11	11,882
Los Alcáceres	15,937	1.09	11,667
Santomera	15,499	1.06	11,347
Fuente Álamo	15,206	1.04	11,132
Puerto Lumbreras	14,183	0.97	10,383
Abarán	13,013	0.89	9,527
Bullas	12,428	0.85	9,099
Beniel	10,966	0.75	8,028
Calasparra	10,820	0.74	7,921
Ceuti	10,527	0.72	7,707
Fortuna	9,796	0.67	7,172
Alguazas	9,211	0.63	6,743
Moratalla	8,480	0.58	6,208
Lorquí	7,018	0.48	5,138
Abanilla	6,580	0.45	4,817
Blanca	6,433	0.44	4,710
Librilla	4,679	0.32	3,425
Pliego	4,094	0.28	2,997
Villanueva	2,339	0.16	1,712
Campos del Rio	2,193	0.15	1,605
Ricote	1,462	0.1	1,070
Albudeite	1,316	0.09	963
Aledo	1,023	0.07	749
Ulea	877	0.06	642
Ojos	588	0.04	430

hydrogen generation to the different towns. Table 5 shows the hydrogen quota assigned to the different towns of Murcia.

In designing a feasible distribution network to cover the FCV demand, four different sizes of hydrogen station have been considered with capacities of 1000, 2000, 5000 and 10,000 Nm³. The size of these hydrogen stations was limited to 10,000 Nm³ because this volume of hydrogen stored doesn't break any local, autonomic, national or European law concerning the storage and handling of dangerous gases. Furthermore, 10,000 Nm³ is a volume of hydrogen of the same order of magnitude than the transported by a tube trailer at pressure of 350 bars [9].

A plausible assignment of hydrogen stations to the different cities/towns in Murcia is shown in Table 6. Bearing in mind the total number of hydrogen stations of Table 6, a hydrogen generation capability of 1,123,000 Nm³ was calculated, which represents an overestimation of only 4.9% with respect to the total capability of hydrogen generation in the province of Murcia. In this regard, a total of 324 hydrogen stations would be necessary to satisfy the hydrogen demanded of 60,000 FCVs (roughly 24% of the total number of vehicles existing in Murcia). In the hypothetical case in which the 100% of the vehicles would be powered with hydrogen, a

Table 6

Hydrogen station distribution considering the capacity of hydrogen generation.

Town	Nm ³	10,000 Nm ³	50,000 Nm ³	2000 Nm ³	1000 Nm ³
Murcia	116,523	25	12	9	0
Cartagena	56,428	12	6	4	0
Lorca	24,470	4	5	2	0
Molina de Segura	17,368	3	2	3	1
Alcantarilla	10,922	3	0	2	0
Mazarrón	9379	0	6	0	0
Cieza	9340	0	4	3	1
Yecla	9224	0	5	0	1
Águilas	9224	0	5	0	1
Torre Pacheco	8568	0	4	2	0
San Javier	8414	0	3	4	1
Totana	7757	0	3	2	3
Caravaca	6986	0	3	2	1
Jumilla	6870	0	2	4	2
San Pedro del Pinatar	6291	0	3	2	0
Las Torres de Cotillas	5635	0	3	0	2
Alhama	5364	0	3	0	1
La Unión	4863	0	0	5	4
Archena	4785	0	0	5	4
Mula	4515	0	0	5	4
Cehejín	4238	0	0	5	4
Los Alcáceres	4207	0	0	5	4
Santomera	4091	0	0	5	4
Fuente Álamo	4014	0	0	5	4
Puerto Lumbreras	3743	0	0	4	5
Abarán	3435	0	0	3	4
Bullas	3280	0	0	3	4
Beniel	2894	0	0	3	4
Calasparra	2885	0	0	3	4
Ceuti	2778	0	0	3	2
Fortuna	2585	0	0	3	2
Alguazas	2431	0	0	3	2
Moratalla	2238	0	0	3	2
Lorquí	1852	0	0	1	4
Abanilla	1736	0	0	0	5
Blanca	1698	0	0	0	5
Librilla	1235	0	0	0	5
Pliego	1080	0	0	0	5
Villanueva	617	0	0	0	2
Campos del Rio	578	0	0	0	2
Ricote	385	0	0	0	2
Albudeite	327	0	0	0	1
Aledo	270	0	0	0	1
Ulea	231	0	0	0	1
Ojos	154	0	0	0	1

total of 112 hydrogen stations would be necessary, each one with a capacity of 10,000 Nm³ (considering an optimization associated with the scale law [7]). This number is lower than the 330 conventional service stations (information provided by the Service Station Association of the Autonomous Region of Murcia) that there is in service in Murcia today. Finally, Fig. 1 shows an overview of how the hydrogen stations could be distributed in Murcia.

3.3. Polluting effects

An undoubted advantage of using hydrogen rather than fossil fuels is the absence of local emissions, because only water and heat are generated during the powering of a vehicle. However, and beyond the above statement, a realistic evaluation of the CO₂ emissions associated with the cycle of hydrogen production (using the electrical power grid) should be carried out, in contrast with the level of emission associated with an internal combustion vehicle (ICV).

The Spanish Electrical Grid Company (Red Eléctrica Española [10]) provides information (in real time) of the CO₂ emissions linked to the electricity produced. This information can help to

estimate the CO₂ emissions (in kg) per kWh generated, considering the mix of energy resources existing in Spain. Table 7 depicts the mean values of CO₂ generated during the *off-peak hours* for several days during 2011. From these values, a mean value of 0.282 ± 0.007 kg/kWh was calculated. In order to have a better correlation between CO₂ emissions and energy resources, it was obtained that a 52% of the CO₂ emissions are associated with power plants using coal as fuel, a 31% are associated with plants of combined cycle and a 17% corresponds to others within special regimes [10].

On the other side, considering that a car uses 8 L of gasoline every 100 km (in a mix driving condition) on average, and that the limit of CO₂ emissions should be below 8.8 kg per gallon according to USA Federal Regulation (<http://www.epa.gov>), in a first approximation (and also realistic) a gasoline car is allowed to exhaust up to 18.6 kg of CO₂ every 100 km. However, to accurately reflect the cycle of CO₂ emissions in a gasoline car, the CO₂ emitted during the production of the gasoline fuel in a refinery should be estimated as well. In this regard, considering the Riegel's Handbook of Industrial Chemistry [25], for each barrel (159 L) of crude oil that passes through a U.S. refinery yield 70.12 L of gasoline, 33.07 L of fuel oil, 14.79 L of kerosene and 8.27 L of residual fuel oil. In addition, from information published by Repsol [26], the ratio between CO₂ emission (in metric tonnes) and refined crude oil (in metric tonnes) was of 0.29 in 2009, which means that on average, 0.36 kg of CO₂ are emitted for each liter of gasoline produced. Hence, considering the emission in an internal combustion vehicle plus the emissions associated with the production of gasoline fuel, a total of 21.5 kg of CO₂ are emitted after covering a distance of 100 km in a ICV.

Thus, considering that a FCV uses 12.8 Nm³ of hydrogen every 100 km, this means that if 5.7 kWh are required for the production of 1 Nm³ of hydrogen and 0.28 kg of CO₂ are emitted in the production of 1 kWh during the *off-peak hours*, that means that 20.7 kg of CO₂ are emitted by a FCV for covering a distance of 100 km.

Hence, from the results obtained above, a FCVs would contribute scarcely in a 4% to the reduction of the CO₂ emissions respect to the level of emissions of a gasoline car (if the hydrogen used by the FCV would come from the electrolysis using the electrical power grid). Thus, considering that new cars are much more efficient (they use less than 5 L of gasoline every 100 km or even less when we refer to hybrid cars that only use 3.5 L of gasoline every 100 km), these new generations of cars become even less polluting than FCVs powered with hydrogen generated electrolytically.

In this context, an estimation of the reduction in the CO₂ emission per year could be carried out for the case in which 167,253 ICVs (the total quantity of FCV that could be refueled with hydrogen generated electrolytically) would be substituted for FCVs. Thus, considering that a vehicle covers a distance of 50 km every day, and

that a FCV reduces in 0.8 kg the emission of CO₂ every 100 km respect to a gasoline car, this means that,

$$\begin{aligned} \text{CO}_2(\text{kg})/\text{year} &= \frac{(\text{ICV}_e - \text{FCV}_e)}{2} * 365 \text{ days} * 167,253 \text{ FCV} \\ &= 24418938 \text{ kg} \end{aligned} \quad (1)$$

where ICV_e and FCV_e correspond to the emission of a internal combustion vehicle (ICV_e = 21.5 kg) and a fuel cell vehicle (FCV_e = 20.7 kg) after covering 100 km, respectively. Thus, considering that 167,253 is the maximum number of FCVs that can be refueled every day, the emissions of CO₂ could be reduced in 24,500 metric tons every year.

Arrived to this point, an interesting aspect to be explored is to evaluate the efficient of the FCV compared with the electric vehicles (EV) in terms of their polluting effects. In this respect, a BMW-i3 car (already on the market) will be used as model of electric vehicle along the below calculations. Thus, considering that 6.2 GWh are available during the off-peak hours (such as it was estimated above), that a BMW-i3 uses 12.9 kWh in covering 100 km [27], and that on average a car covers less than 50 km/day, it means that 96,1240 electric cars could be recharged every day in Murcia. Thus, considering that 0.28 kg of CO₂ are emitted by kWh produced during the off-peak hours, it means that roughly, 3.6 kg of CO₂ are emitted (indirectly in the production of the electric energy used for recharging the batteries) by an electric car for covering 100 km. In this context, considering that there were 690,188 cars registered in Murcia in 2011 (instead of the 961,240 cars that could be recharged every day during the off-peak hours), the emissions of CO₂ could be reduced in a quantity above 2.2 millions of Metric tons per year (after repeating the calculations of Equation (1)) if 690,188 ICV would be substituted by EV.

Obviously, in both cases (FCV and EV), the emissions of CO₂ could be diminished if the percentage of renewable energies in the electrical power grid would be increased during the coming years.

3.4. Impact on the crude oil import

Such as it was mentioned above in the introduction section, the need of developing new cars using emerging technologies is linked to the necessity of reducing the Spanish dependency from the international crude oil markets. In this regard, considering the above mentioned substitution ratio of ICV by FCV or EV, an estimation of the impact of such substitution ratio on the reduction of crude oil import could be carried out. Thus, based on fact that a car uses 8 L of fuel every 100 km on average, and considering that 100 L of fuel can be produced from a barrel of crude oil (such as it was mentioned in the Section 3.3), Murcia could reduce its oil invoice between 6700 and 28,000 barrels per day, supposing that the ICV would be substituted by FCV or EV, respectively, under the terms described above.

These values could be extrapolated to Spain considering that the population of Murcia represents 3.1% of the total vehicles in Spain [20]. Thus, between 216,000 and 903,000 barrels of crude oil per day could be reduced, which represents roughly a reduction between 17% and 70% of the total crude oil consumed in Spain, if ICV could be substituted by FCV or EV respectively, on the base that Spain consumed around 1,278,000 barrels/day in 2013 [28].

4. Conclusions and policy implications

This work has examined the possibility of using Fuel Cell Vehicles in Murcia, considering the state of the art in fuel cell technology, electrolysis, fuel cell vehicles, electric vehicles and the electrical power grid infrastructure existing in Spain.

Table 7

Average CO₂ emissions per kWh generated during the valley hour considering the actual mix of energy resources in Spain [10].

Date	MT/h of CO ₂	MW	kg/kWh
12.01.2011	5000	24,000	0.2083
14.01.2011	7000	24,500	0.2857
27.01.2011	8000	29,000	0.2758
9.02.2011	8700	32,000	0.2718
23.02.2011	4500	30,000	0.1500
24.03.2011	6000	29,000	0.2033
20.04.2011	6300	27,000	0.2333
18.05.2011	6000	27,000	0.2222
22.06.2011	8600	28,500	0.3017
20.07.2011	7000	28,000	0.2500
24.08.2011	10,500	28,750	0.3652
8.09.2011	9600	29,500	0.3254
15.09.2011	8600	30,000	0.2866

From this study, the following conclusions were drawn:

1. Given the fuel consumption of FCV prototypes and the mix of energy resources existing in Spain, the hydrogen generated by electrolysis in Murcia (data that could be extrapolated to the rest of the country) could only supply hydrogen to roughly 25% of the total number of vehicles that exist in Murcia today. This result contrasts with the situation for electric vehicles, for which 100% of the cars existing in Murcia could be replaced by EV. However, setting local plants of renewable energy at hydrogen stations, the capacity of hydrogen generation could be increased to reach a substitution ratio similar to that calculated for EV.
2. To increase the attraction and the interest for FCV, a network of hydrogen stations needs to be developed. A network of hydrogen stations has been proposed, where the distance between any two of these hydrogen stations should never exceed 50 km. In the hypothetical case in which 100% of the vehicles in Murcia could be refueled with hydrogen, only one third of the total number of the conventional gas stations existing today would be necessary.
3. Regarding pollution associated with the replacement of gasoline cars by FCV (using hydrogen generated by electrolysis), it was estimated that Murcia could reduce its CO₂ emissions every year by 24,500 metric tons. This reduction in CO₂ emissions could be increased up to 2.2 million metric tons per year, if ICV were to be replaced by electric cars. These values could be improved, in particular for the FCV, if the electric current obtained from the grid for the hydrogen generation could be implemented with local plants of renewable energy. In any case, any increase in the utilization of renewable energies in the energy mix existing in Spain would have a straight forward translation to the reduction of CO₂ emissions from EV or FCV.
4. The import of crude oil in Spain could be reduced between 15% and 64%, if ICV were to be replaced by FCV or EV, respectively, considering the energy mix existing in Spain.
5. From all of these results, the EV seems to be a more attractive solution than FCV, providing the substitution of ICV by EV doesn't require the establishment of new infrastructure. However, we must also keep in mind that the substitution ratio of ICV by EV or FCV will be based, in part, on the demands of car users, because in general, drivers look for cars with characteristics similar to cars that they are used to driving. Car autonomy seems to be the key aspect that makes the FCV a more plausible option in comparison to EV. This explains the poor acceptance that EV are having among potential drivers, in comparison with other mature technologies with better driving autonomies, such as hybrid cars.

Any implementation of FCV should come from an increase in the contribution of renewable resources to the power grid, which could provide clean electrical power devoted to hydrogen generation, although it is also true that EV seems to be much better positioned than FCV for introduction into the car market. Unfortunately, the policy developed by the Spanish government is moving in the opposite direction since 2012, with dramatic reductions in support of the generation of photovoltaic electricity. This has produced a dramatic slowdown in the establishment of new photovoltaic parks, in comparison with previous years [8].

Acknowledgments

This work was carried out without the financial support from any National nor Local Research Agency, due to the cut in funds for science in Spain. Authors wish to thank the Universidad Politecnica de Cartagena its support to carry out this work. Authors also wish to thank professor Eric Walters at the Rosalind Franklin University and professor Boris Weiss at the Universidad of Chile for their comments and suggestions.

References

- [1] Busby RL. *Hydrogen and fuel cells*. Pennwell Publishing; 2005.
- [2] Srinivasan S. *Fuel cells: from fundamentals to applications*. Springer; 2007.
- [3] Agnolucci P. Hydrogen infrastructure for the transport sector. *Int J Hydrogen Energy* 2007;32(14):3526–44.
- [4] Mertens R. Energy, transport and environment indicators. EUROSTAT. European Commission; 2013. Tech. Rep., Available from: <http://epp.eurostat.ec.europa.eu>.
- [5] Thomas C, James B, Lomax F. Market penetration scenarios for fuel cell vehicles. *Int J Hydrogen Energy* 1998a;23(10):949–66.
- [6] Melaina M. Initiating hydrogen infrastructure: preliminary analysis of a sufficient number of initial hydrogen stations in the US. *Int J Hydrogen Energy* 2003;28(7):743–55.
- [7] Yang C, Ogden J. Analyzing natural gas based hydrogen infrastructure-optimization transition from distributed to centralized H₂ production. Washington, D.C.: National Hydrogen Association; March 29–April 1, 2005.
- [8] Urbina A. Solar electricity in a changing environment: the case of Spain. *Renew Energy* 2014;68:264–9.
- [9] Yang C, Ogden J. Determining the lowest-cost hydrogen delivery mode. *Int J Hydrogen Energy* 2007;32(2):268–86.
- [10] Red Elctrica Española. Demand of electricity. 2012. Tech. Rep. Available from: <http://www.ree.es>.
- [11] Secretaría de Energía. La Energía en España. 2011. Tech. Rep. Available from: <http://www.minetur.gob.es/energia>.
- [12] Instituto Nacional de Estadística. Population and housing census 2011. 2011. Tech. Rep. Available from: <http://www.ine.es>.
- [13] H2Nitidor high pressure generator. 2013. Available from: <http://www.h2nitidor.com>.
- [14] Idroenergy. 2013. Available from: <http://www.idroenergy.com>.
- [15] Pdcmachines. 2013. Available from: <http://www.pdcmachines.com>.
- [16] Honda Motor Co. The zero-emissions electric vehicle of the future. A reality today. 2013. Tech. Rep. Available from: <http://automobiles.honda.com/fc-clarity>.
- [17] Daimler. Daimler: fuel cell drive technology. 2013. Tech. Rep. Available from: <http://www.daimler.com>.
- [18] Thomas C, Kuhn I, James B, Lomax F, Baum G. Affordable hydrogen supply pathways for fuel cell vehicles. *Int J Hydrogen Energy* 1998b;23(6):507–16.
- [19] Thomas C, James B, Lomax F, Kuhn I. Fuel options for the fuel vehicle: hydrogen, methanol or gasoline? *Int J Hydrogen Energy* 2000;25(6):551–67.
- [20] Dirección General de Tráfico. Ministerio del Interior. Anuario Estadístico General del 2011. 2011. Tech. Rep. Available from: <http://www.dgt.es>.
- [21] Zhao J, Melaina M. Transition to hydrogen-based transportation in china: lessons learned from alternative fuel vehicles programs in the United States and China. *Energy Policy* 2006;34:1299–309.
- [22] TK16 from WEH GmbH precision connectors. 2013. Available from: <http://www.weh.com/>.
- [23] Ni J, Ogden J, Yang C, Johnson J. Estimating hydrogen demand distribution using geographical information system (GIS). Washington, D.C. (USA): National Hydrogen Association; March 29–April 1, 2005.
- [24] Pignery A. H₂ IRP-integrated resource planning for the development of hydrogen energy infrastructures. In: *World hydrogen energy conference, Lyon (France)*; 13–16 June 2006.
- [25] Riegel E. *Handbook of industrial chemistry*. Plenum Publishers, New York NY: Kluwer Academic; 2003.
- [26] Repsol-YPF. Repsol: promoting a low carbon strategy. 2012. Tech. Rep. Available from: <http://repsol.webfg.com>.
- [27] BMW automobiles. BMW-i3 tech. rep.. 2013. Available from: <http://www.bmw.com>.
- [28] Carcelén MO. Geoestrategia del petróleo: un factor de riesgo. 2013. Tech. Rep. Available from: <http://www.realinstitutoelcano.org/>.