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Designing a gradual transition to a hydrogen economy in Spain☆

J.J. Brey [a], R. Brey [b,*], A.F. Carazo [b], I. Contreras [b], A.G. Hernández-Díaz [b], V. Gallardo [a]

[a] Hynergreen Technologies, S.A, Av. de la Buhaira 2, 41018 Seville, Spain
[b] Department of Quantitative Methods in Economics, Pablo de Olavide University, Ctra. de Utrera, km 1, 41013 Seville, Spain

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Abstract

The lack of sustainability of the current Spanish energy system makes it necessary to study the adoption of alternative energy models. One of these is what is known as the hydrogen economy. In this paper, we aim to plan, for the case of Spain, an initial phase for transition to this energy model making use of the potential offered by each Spanish region. Specifically, the target pursued is to satisfy at least 15% of energy demand for transport by 2010 through renewable sources. We plan to attain this target gradually, establishing intermediate stages consisting of supplying 5 and 10% of the energy demand for transport by 2006 and 2008, respectively. The results obtained allow us to determine, for each region, the hydrogen production and consumption, the renewable energy sources used to obtain hydrogen and the transport requirements between regions.
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1. Introduction

The Spanish energy system is fundamentally based on imports of natural gas and, above all, crude oil. The main locally available energy resources are nuclear, renewable and, to a lesser extent, coal. The energy situation in Spain in 2004 is shown in Table 1.

This Spanish energy system, based on the use of fossil fuels, leads to two fundamental problems that affect its very survival: energy dependency and gradual decay of the environment [2,3]. This lack of sustainability has led in recent decades to the search for alternative energy models based on the use of renewable energies. In fact, the new *Renewable Energies Plan 2005–2010* [4] sets the target of 12.1% of primary energy consumption being supplied by renewable energies by 2010.

Among the emerging energy models, a possible alternative is what is known as the “hydrogen economy” [5,6], based on the use of hydrogen as a carrier of the energy generated from renewable sources. In this study, we will focus on this alternative, taking into consideration its development for the case of Spain, since the hydrogen economy based on renewable energies can deal with the failings mentioned above. Firstly, it is a system that is mainly based on resources available locally, thus eliminating dependency on other countries. Secondly, to a large extent, it reduces pollutant emissions. These recognized benefits mean that this new system enjoys a great deal of public [7–9] and institutional [10] support at international level, which are fundamental in any technological transition process.

However, a basic problem for developing this type of energy is its high cost in comparison with the current system.[1] The technological procedures for the production, storage, transport and distribution of hydrogen are not yet sufficiently developed [12–14]. Therefore, the main efforts in the area of research into the hydrogen economy are currently directed at developing more efficient procedures in these aspects. Together with them, we should not forget that an additional way to maximize environmental gains and minimize the cost of implementing a hydrogen based economy consists of carrying out correct planning of the transition process. Spain is made up of 17 regions, known as *Autonomous Communities*, two of which are archipelagos. Multi-objective programming would be able to take advantage

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* Corresponding author. Tel.: +34 954 97 79 76; fax: +34 954 34 93 39.
E-mail address: rbresan@upo.es (R. Brey).

[1] This superiority of the traditional system in financial terms is only under a market economy system. If we incorporate as a production cost the negative effects on the environment generated by the use of fossil fuels (externalities), the hydrogen economy could result more competitive, as shown in Ref. [11].

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Table 1
Consumption, production and level of energy self-sufficiency in Spain (2004)

	Primary energy consumption		Energy production (ktep)		Level of self-sufficiency
	ktep	%	ktep	%	%
Coal	21034	14.8	6922	20.9	32.9
Oil	71055	50.0	255	0.8	0.4
Natural Gas	24672	17.3	310	0.9	1.3
Nuclear	16576	11.6	16576	50.2	100.0
Renewable	8982	6.3	8982	27.2	100.0

Source: Ref. [1].

of the positive points that each region has to offer in the production of the different types of renewable energies to satisfy its own energy demand, as well as those of less fortunate regions.

At international level, although from the institutional point of view the importance of planning has been recognized on numerous occasions as a study field [10,15], the first works that carry out any type of planning in the field of hydrogen are fairly recent. Most of these studies have been focused on a partial aspect of the process, such as optimum distribution of hydrogen fuelling stations to supply a specific region, or the design of hydrogen transport infrastructures [16–19]. There are also other works that make a more global study of the process [20], usually applied to one specific country [21–24]. The study presented here is among the latter.

In this paper, our aim is to plan the first stage in the process of transition to a hydrogen economy, setting the target of supplying successively 5, 10 and 15% of energy demand for transport by 2006, 2008 and 2010, respectively, through the use of hydrogen from renewable sources. We are focusing on the transport sector for two reasons. Firstly, in 2004 the transport sector was the one that demanded the most energy in Spain, with consumption of 37,828 ktep (36.2%), followed by the industry sector with 37,590 ktep (36.0%) and *miscellaneous uses* with 29,016 ktep (27.8%) [1]. Secondly, the transport sector is the area of highest development and application of hydrogen as an energy vector at European level.

The structure of this paper is as follows. In Section 2, we study the feasibility of the target set. In Section 3, we show the model used to plan the transition process in Spain. Section 4 contains the procedure followed for resolving the model, the results of which are discussed in Section 5. Finally, Section 6 contains the main conclusions.

2. Feasibility of the proposed transition phase

Prior to carrying out gradual planning of the transition process with the target of supplying 15% of energy demand for transport by 2010, the feasibility of achieving this target has to studied. This feasibility depends on two factors: the development in Spain of the supply of energy from renewable sources and the energy demand for transport.

To calculate supply, we will consider in this paper the five renewable energies most extended in Spain in terms of their technological development level, their effective implantation, or for the current institutional interest in them. In particular, we will consider photovoltaics, wind power, mini-hydraulic, high-temperature thermal solar and biomass. Table 2 contains the target values for each of these five types in the Spanish regions

Table 2
Target set in Spain for renewable energies by 2010

Regions	Photovoltaics (MWp)	Wind power (MW)	Mini-hydraulic (MW)	Thermal solar (MW)	Biomass (tep)
Andalucía	51.2	2200	228	300	88000
Aragón	16.8	2400	234	0	88000
Asturias	9.3	450	100	0	44000
Baleares	17.7	50	0	0	44000
Canarias	17.2	630	2	0	0
Cantabria	9.2	300	59	0	220000
Castilla-León	28.3	2700	354	50	330000
Castilla-Mancha	13.4	2600	145	50	176000
Cataluña	56.6	1000	282	0	330000
C. Valenciana	34.1	1600	58	0	0
Extremadura	13.4	225	32	50	176000
Galicia	24.0	3400	317	0	220000
La Rioja	9.2	500	56	0	0
Madrid	31.7	50	49	0	22000
Murcia	20.1	400	22	50	220000
Navarra	19.6	1400	195	0	154000
País Vasco	26.1	250	66	0	88000
Total	398	20155	2199	500	2200000

Source: Ref. [4].

proposed in the Renewable Energies Plan 2005–2010 [4]. As for the hydrogen production processes, we will consider the combination of the above five renewable technologies with an electrolysis process for the first three and reforming and gasification, respectively, for the fourth and fifth.

To obtain energy demand projections for 2010, we use the methodology proposed in Ref. [25] as a base. In this methodology, the demand for hydrogen for transport depends directly on the estimated population for each region. An estimate of the total value of demand for any Community, which we call D_i, is obtained by multiplying the estimated population by that date by the number of vehicles per person and by unit consumption of a vehicle per unit of time, i.e.

$$D_i = \text{Population} \times \text{Vehicle ownership (vehicles/person)} \times \text{Fuel use (kg } H_2\text{/year)}$$

Population data is calculated by the Spanish National Institute of Statistics [26]. The rate of ownership (number of vehicles per person) is the value calculated for each region in 2004 taking into consideration all light duty vehicles [27]. A vehicle's annual consumption is calculated assuming that a car travels an average of 27,000 km year^{-1} and consumes 1 kg of hydrogen every 117 km [25]. Demand projections for 2010 are contained in Table 3.

The conjunction of these energy supply and demand projections for 2010 show that Spain can satisfy over 15% of its energy demand for transport by energy from renewable sources (approximately 32.42%). Therefore, the targets set in this study are feasible and allow us to approach planning of this process through a mathematical model.

In the next section, a multi-objective programming model is developed to enable, for the time-period considered, the planning of the investment in renewable energies, and the production and distribution of the hydrogen generated among the different Spanish regions. For this purpose, economic, social and environmental criteria will be simultaneously taken into consideration. In particular, we will consider, for each region, the energy demand from the vehicle pool, level of contamination, possibilities of transporting the hydrogen among the regions and governmental preferences for the development of the different types of energy considered for generating hydrogen.

Table 3
Hydrogen demand (D_i) for transport in kg, for the three periods under consideration

Regions	2006	2008	2010
Andalucía	976,235,875.36	993,044,514.67	1,005,111,779.23
Aragón	158,010,785.88	159,395,791.52	159,744,068.53
Asturias	123,988,136.23	123,249,407.39	122,158,567.56
Baleares	189,103,337.69	196,005,414.42	200,340,961.41
Canarias	282,495,484.80	290,391,165.67	295,456,116.00
Cantabria	66,452,446.98	67,296,045.36	67,896,353.43
Castilla-León	314,266,498.69	313,539,955.14	311,739,346.31
Castilla-Mancha	243,650,891.70	249,441,311.06	253,723,266.98
Cataluña	942,171,912.29	964,682,554.26	977,335,702.33
C. Valenciana	638,856,419.39	658,993,428.49	671,954,458.03
Extremadura	132,130,891.79	132,483,816.55	132,387,452.32
Galicia	295,180,258.11	294,800,171.49	293,344,152.36
La Rioja	853,434,514.00	873,890,478.71	883,674,342.30
Madrid	158,341,489.81	163,325,444.49	166,574,928.34
Murcia	83,857,786.45	85,327,457.82	86,219,054.64
Navarra	254,976,154.05	255,552,734.76	255,472,876.27
País Vasco	29,980,903.95	30,661,940.57	31,053,619.62
Total	5,743,133,787.18	5,852,081,632.34	6,180,911,527.05

Source: own statistics.

3. Model for gradual transition to a hydrogen economy in Spain

Planning of the gradual transition to a hydrogen economy is characterized by the existence of multiple conflicting interests, decision variables and constraints. The difficulty in finding a single solution leads to the adoption of specific techniques to determine the set of efficient solutions that balances all aspects. The decision-maker will select the best solution from them according to his/her preferences. Therefore, this research is converted into a problem that can be approached from the Multiple Criteria Decision Making theory.

In this paper, we focus on planning hydrogen production and consumption at regional level based on renewable sources for the purpose of satisfying around 15% of the Spanish national demand for vehicle fuel by 2010, with the two intermediate targets that have already been mentioned for 2006 (5%) and 2008 (10%). As mentioned earlier, the hydrogen production technologies considered (known as group J in the model) are:

1. Photovoltaic energy + electrolysis.
2. Wind power + electrolysis.
3. Mini-hydraulic power + electrolysis.
4. High-temperature thermal solar energy + reforming.
5. Biomass + gasification.

In addition, we consider the following relevant aspects: cost, energetic preferences and environmental equity.

3.1. Cost

Obviously, regardless of any other criterion, it is preferable to carry out the transition process with the lowest possible economic cost. Within this concept, we take into consideration the strictly economic costs of energy production from renewable sources, its subsequent transformation into hydrogen, and its distribution. Taking the cost criterion exclusively into account, it is equivalent to a cost-effectiveness analysis. In other words, it is a question of achieving a specific objective, covering a certain level of energy demand for transport through the use of hydrogen as fuel, at the lowest possible cost.

The increase in the production of each type of renewable energy considered over the 2004–2006–2008–2010 period will have an impact on its production costs. We have reflected this dynamic nature of costs using experience curves [28]. These curves provide a quantitative relationship between the price and the cumulative production or use of a technology, showing how the price decreases with cumulative production. The curve is represented by the following mathematical expression

$$C_j(X) = C_{0_j} X_j^{b_j}, \tag{1}$$

where X_j represents cumulative production of hydrogen and C_j, C_{0_j} and b_j denote, for each technology j, the cost per unit, the cost of the first unit and the experience index, respectively. The experience index may be obtained from what is known as the learning rate, LR_j, which represents the rate at which the costs are reduced with each doubling of the units produced for each type of technology, through the following expression $LR_j = 1–2^{b_j}$. We have estimated the experience curves from the learning rates used in Ref. [29] in the European Union (see Table 4) and the C_{0_j} have been obtained from Ref. [30].

Thus, the objective of minimizing the total cost of production and transport of hydrogen can be written as the following non-linear equation

$$\text{Min} \sum_{i \in I} \sum_{j \in J} C_{0_j} \int_0^{X_{ij}} t^{b_j}\, dt + \sum_{i \in I} \sum_{i' \in I} TC_{ii'} T_{ii'}, \tag{2}$$

where X_{ij} denote the kilograms of hydrogen produced in region i by process j, $TC_{ii'}$ and $T_{ii'}$ represent transport costs per unit and kilograms of hydrogen transported from region i to region i', respectively, with $i, i' \in I$. It is important to point out that the T_{ii} represent the quantities produced and consumed in the same region. In such cases, the transport costs TC_{ii} are equal to zero.

Transport costs ($TC_{ii'}$) have been calculated from Ref. [31] where different costs depending on the number of kilometres covered and the method of transport used are given. In our paper, we only consider hydrogen transport by road except for insular regions, that is, for the Baleares Islands and Canarias Islands. In these cases, the transport is assumed from the supplier region to the nearest seaport by road and from there to the islands by ship. These data are available from the corresponding author.

At present, there are very varied existing procedures for obtaining energy from renewable sources and for its subsequent transformation into hydrogen. Taking financial criteria exclusively into account would undoubtedly lead only to the development of the most economically profitable procedures. This trend would reduce the future possibilities of expansion of those procedures which are at a more primitive stage of development, for which a high cost of initial research and putting into operation is necessary. Due to this, we include another aspect to be taken into consideration in the planning process: energetic preferences.

Table 4
Learning rate by technology

Technology	Learning rate
Photovoltaic energy (%)	15
Wind power (%)	9
Mini-hydraulic power	Not cost decreased considered
High-temperature thermal solar energy (%)	15
Biomass (%)	5

Source: Ref. [28].

3.2. Energetic preferences

By energetic preferences, we will refer to the actions of governments which, whether through regulations, through bonuses or subsidies, try to assist the development of sources of energies which are not profitable in the market system, but which are of unquestionable future benefit to society. When planning the transition it would be preferable to aim for a transition to a hydrogen economy which is not exclusively based on certain sources of renewable energies, abandoning the rest. The second aspect considered in this planning process consists of minimizing the higher of the deviations (denoted by n_{ij}) from real productions with respect to the energetic preferences of the government by region for each renewable energy sources. Formally:

$$\text{Min} \underset{i \in I, j \in J}{\text{Max}} \{n_{ij}\}. \tag{3}$$

These deviations n_{ij} for each region and process are defined by the constraints

$$X_{ij} + n_{ij} = MO_{ij} - IO_{ij}, \quad \text{for } i \in I \text{ and } j \in J, \tag{4}$$

where MO_{ij} denotes hydrogen production by process j in region i equivalent to the production targets for renewable energies established by the government for 2010 (Table 2), and IO_{ij} current hydrogen production using process j in region i. In these constraints, n_{ij} values are obtained as the differences between the maximum hydrogen production possible by process j in region i according to government preferences ($MO_{ij} - IO_{ij}$) and hydrogen production for the same process and region established in the planning process (X_{ij}). In this paper, IO_{ij} has been obtained assuming that all energy production from renewable sources in 2004 [4] is transformed into hydrogen (Table 5).

3.3. Environmental equity

The final objective of supplying a specific percentage of national energy demand for transport by hydrogen from renewable sources does not necessarily imply that this reduction has to be the same in all regions. It could happen that this reduction at national level is mainly achieved on the basis of just a few regions, those with a higher potential for energy from renewable sources, since transporting hydrogen would involve a cost. In this way, the environmental benefits derived from higher hydrogen consumption would be concentrated in a few regions, regardless of their initial environmental situation. Thus, regions with a low pollution level could see their levels decrease even further, while other regions would remain at critical levels.

With this aspect, which is called as *environmental equity*, what we are aiming for is to guarantee a certain level of hydrogen consumption in each region and also to allow differences in the level of consumption between regions according to their level of pollution. The idea of this criterion is that a reduction of pollution produces a higher increase in well being in regions which have initially higher pollution levels. In other words, the marginal utility brought about by the reduction of pollution will be higher

Table 5
Power capacity in Spain in 2004 from renewable energies

	Photovoltaics (MWp)	Wind power (MW)	Mini-hydraulic (MW)	Thermal solar (MW)	Biomass (tep)
Andalucía	7.860	350.000	197.700	0.000	0.000
Aragón	0.673	1154.000	194.300	0.000	0.000
Asturias	0.340	145.000	90.300	0.000	3600
Baleares	1.327	3.000	0.000	0.000	0.000
Canarias	1.196	139.000	1.400	0.000	0.000
Cantabria	0.068	0.000	53.500	0.000	0.000
Castilla-León	2.729	1543.000	263.800	0.000	0.000
Castilla-Mancha	1.778	1534.000	105.100	0.000	36000
Cataluña	4.107	94.000	232.400	0.000	50400
C. Valenciana	2.827	21.000	44.700	0.000	0.000
Extremadura	0.538	0.000	25.200	0.000	0.000
Galicia	0.506	1830.000	214.900	0.000	64500
La Rioja	0.151	356.000	45.900	0.000	0.000
Madrid	2.384	0.000	45.500	0.000	4500
Murcia	1.032	49.000	18.300	0.000	51200
Navarra	5.443	854.000	161.200	0.000	0.000
País Vasco	2.400	85.000	54.800	0.000	18000
Total	35.359	8157.000	1749.000	0.000	228200

Source: Ref. [4].

in Communities which, due to their production system or other reasons, currently have higher pollution levels. Hence, it seems reasonable to encourage the use of hydrogen in Communities with higher pollution levels.

The constraints in (5) indicate that all hydrogen transported to a region i, $\sum_{i' \in I} T_{i'i}$, has to be sufficient to supply the hydrogen consumption required in that region. As previously mentioned, the T_{ii} represent the quantities of hydrogen that are produced and consumed in the same region. These restrictions are introduced as an idea of aiming for some level of environmental equity since they allow differences between regions in hydrogen consumption depending on the pollution that already exists in each of them. Hydrogen consumption for each community is calculated as a specific proportion of total energy demand (D_i) for transport in the region. This proportion varies according to the percentage p of reduction pursued for the total in Spain (in our case 5, 10 and 15%, respectively, in each of the periods in question, 2004–2006, 2006–2008 and 2008–2010). The percentage differences allowed in hydrogen consumption between regions are established by using the parameters *range* and β_i. The value of *range* determines the maximum deviation allowed for a region with respect to the value p (in our case, *range* = 2%, which is why the percentage hydrogen consumption in a region, with respect to regional energy demand, will vary between 3 and 5% in 2006, 8 and 12% in 2008 and 13 and 17% by 2010). The parameter β_i introduces the differences between Communities in the interval established previously according to the CO_2 emissions in each region.

$$\sum_{i' \in I} T_{i'i} \geq D_i(p + 2\,\text{range}\,\beta_i - \text{range}), \quad \text{for } i \in I. \tag{5}$$

The value of β_i is determined by the final pollution in each region, measured by the difference between initial emissions P_i and emissions avoided by the hydrogen consumed, $\text{AP}\sum_{k \in I} T_{ki}$, where AP denotes CO_2 emissions avoided by consumption of 1 kg of hydrogen. So, the specific values of β_i are

$$\beta_i = \frac{P_i - \text{AP}\sum_{k \in I} T_{ki} - \underset{l \in I}{\text{Min}}\left\{P_l - \text{AP}\sum_{k \in I} T_{kl}\right\}}{\underset{l \in I}{\text{Max}}\left\{P_l - \text{AP}\sum_{k \in I} T_{kl}\right\} - \underset{l \in I}{\text{Min}}\left\{P_l - \text{AP}\sum_{k \in I} T_{kl}\right\}}. \tag{6}$$

The parameters β_i have been normalized so that they vary between 0 and 1; the minimum for all regions as whole is subtracted from the value for each region and the result is divided between the distance between the maximum and minimum of these final pollution values.

Initially, the regions have a specific value of β_i according to their relative pollution levels. The more polluted the region, the higher its value of β_i. Values of β_i close to 0 indicate that this region is in an advantageous position with respect to other regions in terms of final pollution, whereas values of β_i close to 1 are associated with regions whose relative position regarding final pollution by CO_2 is less favourable. A higher value of this parameter will lead to a larger hydrogen demand to be satisfied in this region. Thus, the reduction of pollution levels will be different in each region. This will change the final value of the parameter to reflect the new relative position of the region in terms of pollution.

For the case of Spain, pollutant gas emissions in 2004 (P_i in tonnes of CO_2) in each region are obtained from Ref. [32]. The pollution avoided by vehicles by replacing fossil fuels with hydrogen is 171 $gCO_2\,km^{-1}$ [33]. As in Ref. [25], we have assumed that a vehicle travels 27,000 km year^{-1} and consumes 0.6 kg H_2/day.

3.4. Technical constraints

For resolution of the model, we need to consider a set of logical constraints. Firstly, constraint (7) is introduced to satisfy at least the percentage required (p) of the total demand for the country

$$p\left(\sum_{i \in I} D_i\right) \leq \sum_{i \in I}\sum_{i' \in I} T_{ii'}. \quad (7)$$

The group of constraints given by (8) restricts, for each region $i \in I$, the volume of hydrogen transported from this region to the rest of the regions so that no more than the sum of the hydrogen produced and initial production through all the processes can be transported

$$\sum_{i' \in I} T_{ii'} \leq \sum_{j \in J}(X_{ij} + \mathrm{IO}_{ij}), \quad \text{for } i \in I. \quad (8)$$

Finally, we include a set of non-negative constraints for the decision variables

$$X_{ij}, T_{ii'}, n_{ij} \geq 0, \quad \text{for } i \in I \text{ and } j \in J. \quad (9)$$

3.5. Model

The model aims to minimize the two objectives proposed (total cost of transition and deviation of the energetic targets set by the government in Ref. [4]), subject to the set of constraints described above. In each of the three periods considered, the model is solved by changing the percentage of demand satisfied. The model is expressed as follows

$$\mathrm{Min}\left(\sum_{i \in I}\sum_{j \in J} C_{0_j}\int_0^{X_{ij}} t^{b_j}\,\mathrm{d}t + \sum_{i \in I}\sum_{i' \in I}\mathrm{TC}_{ii'}T_{ii'},\ \underset{i \in I, j \in J}{\mathrm{Max}}\{n_{ij}\}\right) \quad (10)$$

Subject to

Set of constraints (4)–(9).

4. Solving the model

As previously discussed, multi-objective optimization problems do not have usually a single optimum solution optimizing all the objectives simultaneously. The reason is that the objectives are usually in conflict with each other. As a result, the purpose of these problems is to obtain a group of efficient solutions. There are various techniques for calculating the group of efficient points: aggregation of objectives, ∈-constraints, Compromise Programming, etc. (see Ref. [34]). In this paper, the ∈-constraints method has been chosen for its simplicity of formulation. This method transforms the multi-objective problem into a single-objective problem, including the remaining objectives as constraints in the problem.

In the specific case of our model, we calculate, for each of the three problems, the variation range of the second objective, $[f_2^{\min}, f_2^{\max}]$, solving the following two expressions:

$$f_2^{\min} = \mathrm{Min}\ \underset{i \in I, j \in J}{\mathrm{Max}}\{n_{ij}\}$$

Subject to (11)

Set of constraints (4)–(9),

and

$$f_2^{\max} = \mathrm{Max}\ \underset{i \in I, j \in J}{\mathrm{Max}}\{n_{ij}\}$$

Subject to (12)

Set of constraints (4)–(9).

For each value $f_2^* \in [f_2^{\min}, f_2^{\max}]$ we have obtained an efficient solution by solving the following single-objective problem:

$$\mathrm{Min}\sum_{i \in I}\sum_{j \in J} C_{0_j}\int_0^{X_{ij}} t^{b_j}\,\mathrm{d}t + \sum_{i \in I}\sum_{i' \in I}\mathrm{TC}_{ii'}T_{ii'}$$

Subject to (13)

$$\underset{i \in I, j \in J}{\mathrm{Max}}\{n_{ij}\} \leq f_2^*$$

Set of constraints (4)–(9).

Using expression (13) of the model, and with specific data for the case of Spain for each of the three periods, we obtained the results contained in the next section.

5. Results

First of all, we will show the set of efficient solutions obtained for the first problem solved, consisting of satisfying 5% of national demand by 2006. Then we will focus the study on a specific solution from this set for each of the three problems under consideration, in order to compare them and show the type of information provided by the model.

Fig. 1 shows an approximation of the set of efficient solutions for 2006, obtained on solving (13) at 11 equidistant points in the

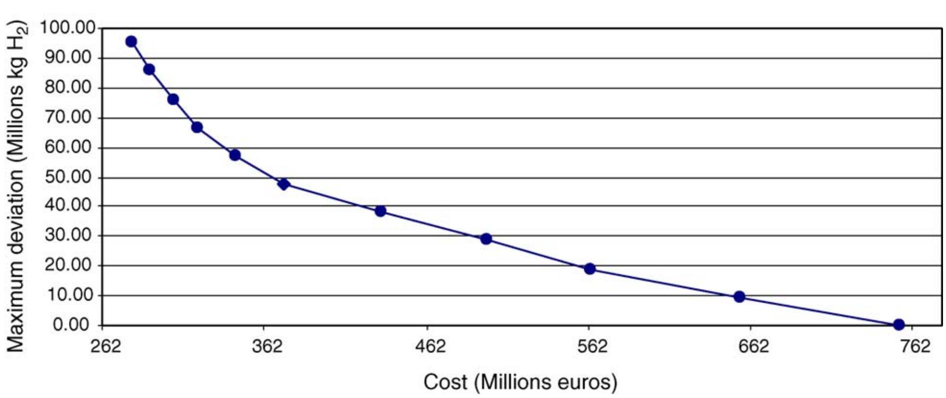

Fig. 1. Set of efficient solutions for 2006.

Table 6
Production (in kilograms of hydrogen) to satisfy the 5% in 2006

Regions	Photovoltaics	Wind power	Mini-hydraulic	Thermal solar	Biomass	Total
Andalucía	948,966.40	95,104,460.00	0.00	60,815,740.00	0.00	156,869,166.40
Aragón	351,760.70	64,054,140.00	0.00	0.00	0.00	64,405,900.70
Asturias	195,349.70	15,679,380.00	0.00	0.00	0.00	15,874,729.70
Baleares	358,979.70	2,416,167.00	0.00	0.00	3,695,513.00	6,470,659.70
Canarias	350,885.70	25,241,240.00	0.00	0.00	0.00	25,592,125.70
Cantabria	199,943.60	15,422,340.00	0.00	0.00	13,744,920.00	29,367,203.60
Castilla-León	560,017.10	59,478,840.00	0.00	10,135,960.00	44,393,500.00	114,568,317.10
Castilla-Mancha	254,632.80	54,800,730.00	0.00	10,135,960.00	0.00	65,191,322.80
Cataluña	1,148,035.00	46,575,480.00	0.00	0.00	30,350,880.00	78,074,395.00
C. Valenciana	683,614.60	81,172,940.00	0.00	0.00	0.00	81,856,554.60
Extremadura	281,102.30	11,566,760.00	0.00	10,135,960.00	1,485,490.00	23,469,312.30
Galicia	513,859.40	80,710,270.00	0.00	0.00	0.00	81,224,129.40
La Rioja	198,631.10	7,402,726.00	0.00	0.00	0.00	7,601,357.10
Madrid	641,613.30	2,570,391.00	203, 443.70	0.00	4,875,910.00	8,291,358.00
Murcia	416,293.90	18,044,140.00	0.00	10,135,960.00	0.00	28,596,393.90
Navarra	310,634.50	28,068,670.00	0.00	0.00	0.00	28,379,304.50
País Vasco	518,453.30	8,482,290.00	0.00	0.00	0.00	9,000,743.30
Total	7,932,773.10	616,790,964.00	203, 443.70	101,359,580.00	98,546,213.00	824,832,973.80

Source: own statistics.

interval [$f_2^{\min}$, $f_2^{\max}$]. The decision-maker will select a specific solution from this space depending on the intensity of his/her preferences about the targets under consideration.

In this figure, we can see the trade-off existing between the targets under consideration (the cost of replacing 5% of fuel for transport with hydrogen and maximum deviation with respect to the government's energetic preferences). The first point on the left shows the solution obtained when the decision-maker only considers the target of minimizing the cost (€280.39 million). The first point on the right represents the solution obtained when the decision-maker wishes to minimize deviations as much as possible with respect to energetic preferences, ignoring the cost target (€754.42 million). This situation would lead to production of more than the 5% established as a target in this study, to achieve making the values n_{ij} zero. The points located between both extremes represent intermediate situations between the previous two extreme cases.

Once the set of possible solutions has been shown, we will focus the study on one specific solution. The objective is to show the level of information provided by the model in each solution and the changes that take place between the 3 years under consideration. The point analyzed is the sixth point represented and it shows a compromise solution between the two objectives under consideration.

Comparison of the solutions obtained for each year is made with respect to levels of hydrogen production, hydrogen transport levels forecast among the regions and pollution levels avoided by considering hydrogen as a fuel for motor vehicles.

Tables 6–8 show production of hydrogen from each type of renewable energy by region for each of the three periods in

Table 7
Increase in production (in kilograms of hydrogen) to satisfy the 10% in 2008

Regions	Photovoltaics	Wind power	Mini-hydraulic	Thermal solar	Biomass	Total
Andalucía	0.00	0.00	0.00	0.00	742,744.90	742,744.90
Aragón	0.00	0.00	0.00	0.00	742,744.90	742,744.90
Asturias	0.00	0.00	0.00	0.00	0.00	0.00
Baleares	0.00	0.00	0.00	0.00	8,563,917.00	8,563,917.00
Canarias	0.00	0.00	0.00	0.00	0.00	0.00
Cantabria	0.00	0.00	0.00	0.00	24,176,330.00	24,176,330.00
Castilla-León	0.00	0.00	0.00	0.00	24,176,330.00	24,176,330.00
Castilla-Mancha	0.00	0.00	0.00	0.00	15,231,170.00	15,231,170.00
Cataluña	0.00	0.00	0.00	0.00	24,176,330.00	24,176,330.00
C. Valenciana	0.00	0.00	0.00	0.00	0.00	0.00
Extremadura	0.00	0.00	0.00	0.00	24,176,330.00	24,176,330.00
Galicia	0.00	0.00	0.00	0.00	19,764,440.00	19,764,440.00
La Rioja	0.00	0.00	0.00	0.00	0.00	0.00
Madrid	0.00	0.00	0.00	0.00	0.00	0.00
Murcia	0.00	0.00	0.00	0.00	23,633,750.00	23,633,750.00
Navarra	0.00	0.00	0.00	0.00	19,327,030.00	19,327,030.00
País Vasco	0.00	0.00	4033.34	0.00	2,231,535.00	2,235,568.34
Total	0.00	0.00	4033.34	0.00	186,942,651.80	186,946,685.14

Source: own statistics.

Table 8
Increase in production (in kilograms of hydrogen) to satisfy the 15% in 2010

Regions	Photovoltaics	Wind power	Mini-hydraulic	Thermal solar	Biomass	Total
Andalucía	0.00	0.00	0.00	0.00	11,888,060.00	11,888,060.00
Aragón	0.00	0.00	0.00	0.00	18,481,270.00	18,481,270.00
Asturias	0.00	0.00	0.00	0.00	0.00	0.00
Baleares	0.00	0.00	0.00	0.00	0.00	0.00
Canarias	0.00	0.00	67, 814.56	0.00	0.00	67,814.56
Cantabria	0.00	0.00	0.00	0.00	13,820,900.00	13,820,900.00
Castilla-León	0.00	0.00	0.00	0.00	11,487,840.00	11,487,840.00
Castilla-Mancha	0.00	0.00	0.00	0.00	11,888,050.00	11,888,050.00
Cataluña	0.00	0.00	3, 390, 728.00	0.00	23,375,890.00	26,766,618.00
C. Valenciana	0.00	0.00	881, 589.40	0.00	0.00	881,589.40
Extremadura	0.00	0.00	0.00	0.00	18,073,730.00	18,073,730.00
Galicia	0.00	0.00	0.00	0.00	11,673,440.00	11,673,440.00
La Rioja	0.00	0.00	0.00	0.00	0.00	0.00
Madrid	0.00	0.00	0.00	0.00	0.00	0.00
Murcia	0.00	0.00	0.00	0.00	18,096,120.00	18,096,120.00
Navarra	0.00	0.00	0.00	0.00	11,692,920.00	11,692,920.00
País Vasco	0.00	0.00	741, 926.90	0.00	12,111,670.00	12,853,596.90
Total	0.00	0.00	5, 082, 058.86	0.00	162,589,890.00	167,671,948.86

Source: own statistics.

question. In the solution for the first year (Table 6) we present the production values for each of the five types of energy (X_{ij}), while in the solutions for the next two periods, we only show the increases in production with respect to the previous year's solution.

The model suggested also allows forecast of energy requirements for each Spanish region. In the solution obtained for the first period, only Madrid uses up all its resources, making it necessary for it to transport to meet its demand. However, there are several Communities that would only use up some of their lower cost renewable sources, particularly photovoltaics and wind power. It is interesting to note that in the compromise solution that we analyze there is a production surplus over and above the 5% of demand required. However, the excess production reached in the compromise solution in these regions is not mainly transported to other Communities, since it is more expensive to transport hydrogen than to produce it in the regions that require it.

Transport requirements increase as the percentage demand to be met gets higher. Thus, to supply 10% by 2008, the Baleares Islands would join Madrid in terms of transport requirements, while by 2010, if we want to meet 15% of national demand, the regions that need to import from other Communities are, in addition to the previous two, the Canarias Islands, and C.

Table 9
Estimated environmental gains

Region	Initial pollution (%)	2006		2008		2010	
		Final demand satisfied (%)	Avoided pollution (t CO_2)	Final demand satisfied (%)	Avoided pollution (t CO_2)	Final demand satisfied (%)	Avoided pollution (t CO_2)
Andalucía	13.71	7.00	1,440,683.45	12.00	2,512,266.61	17.00	3,602,293.12
Aragón	4.93	4.53	150,855.81	9.55	320,828.33	14.59	491,419.32
Asturias	8.10	5.24	136,873.94	10.26	266,540.10	15.32	394,480.34
Baleares	2.33	3.52	140,280.45	8.51	351,857.48	13.54	571,840.56
Canarias	3.83	4.00	238,504.35	9.00	551,142.52	14.02	873,462.32
Cantabria	1.33	3.22	45,137.35	8.22	116,665.94	13.26	189,749.26
Castilla-León	11.14	6.33	419,380.24	11.37	751,439.33	16.41	1,078,502.56
Castilla-Mancha	6.52	4.80	246,668.23	9.90	520,733.67	15.03	803,836.79
Cataluña	13.67	6.75	1,340,411.23	11.74	2,388,615.63	16.74	3,448,538.10
C. Valenciana	7.05	5.03	678,115.84	9.99	1,387,849.14	15.03	2,129,148.42
Extremadura	2.18	3.46	96,339.37	8.41	234,846.92	13.42	374,529.89
Galicia	9.16	5.72	355,679.16	10.43	648,284.64	15.47	956,651.77
La Rioja	0.57	3.00	539,768.11	8.00	1,473,882.15	13.00	2,421,872.98
Madrid	6.63	4.77	159,274.45	9.74	335,245.01	14.71	516,738.36
Murcia	2.14	3.46	61,171.45	8.43	151,707.29	13.44	244,377.23
Navarra	1.44	3.17	170,287.66	8.30	446,967.35	13.16	708,940.76
País Vasco	5.26	4.52	28,577.66	9.55	61,728.67	14.58	95,439.64
Total			6,248,008.75		12,520,600.81		18,901,821.42

Source: own statistics.

Valenciana. Given that the cost of transport of 1 kg of hydrogen is higher than the cost of its production (regardless of the process used), central government and the regional governments of these Communities should promote the production of renewable energies to avoid having to transport hydrogen from neighbouring regions.

Table 9 compares the results obtained for the compromise solution in each year taken into consideration according to pollution avoided. The *Initial Pollution* column represents the percentage pollution in each region with respect to the national total in 2004. The constraints cause the least polluted regions (for example, La Rioja with 0.57% of Spanish pollution) to yield part of the basic demand in favour of the most polluted regions in each of the three periods (in the case of La Rioja, covering only 3, 8 and 13% of initial demand corresponding to each of the three problems under consideration). Thus, the *Final demand satisfied* column contains the percentages of the final demand satisfied in each region for each period. Finally, the *Avoided pollution* column shows the tons of CO_2 that will be avoided in each region if the previous percentages are met.

Environmental gains in this first transition phase aimed at a hydrogen economy are obvious. For the first solution, supply of approximately 5% of the energy demand for transport by hydrogen from renewable energies will bring about a reduction of pollution of 6,248,008 tonnes of CO_2 by 2006, which represents a drop of 1.50% in total pollution in 2004. In the next two periods this percentage rises, respectively, to 3.01% by 2008 and 4.54% by 2010.

6. Conclusions

The energy dependency and environmental decay presented by the current Spanish energy system make it necessary to create new alternatives. One of them is the transition to a hydrogen economy. In this paper we have looked at the first phase of the transition process in which we have considered substitution of around 15% of energy demand for transport with hydrogen obtained from renewable sources by 2010. To do this, we have considered two intermediate stages consisting of meeting 5 and 10% of the energy demand for transport in 2006 and 2008, respectively.

First of all, we have studied the feasibility of this target. The projections made for 2010, both for supply of energy from renewable sources and for energy demand for transport, confirm that it is a target that can be reached. The target for energy production from renewable sources established by the Spanish government for 2010 [4] can satisfy around 32.42% of the energy demand for transport estimated for Spain by 2010.

The next question studied was that of planning this process. This planning was carried out on the basis of two fundamental objectives: minimizing the cost of the process and minimizing deviations with respect to the government preferences expressed in Ref. [4]. The study has shown that the use of a mathematical model may help to design this transition process. Solving the model obtains a set of efficient solutions. Selection of one of them depends on the preferences of the decision-maker with respect to the above objectives. Each solution determines, for each region, the value of different variables: the quantity of hydrogen produced and consumed by each region, as well as the quantity and type of each of the renewable energy sources used, and the quantity of CO_2 avoided by using hydrogen as a fuel for transport in approximately 15% of motor vehicles.

To show the relevance of the model, we have studied a specific solution for each of the 3 years, consisting of a compromise solution between the two objectives proposed. The results for these solutions have shown the high environmental benefits derived from this first phase of transition to a hydrogen economy. By 2010, pollution will have dropped by an amount equivalent to 4.54% of the total pollution in 2004. Furthermore, the model created allows consideration of inequalities between Communities in terms of pollution level and promotion of hydrogen consumption in the regions with the highest pollution levels.

For the three solutions studied, most Spanish regions are self-sufficient for supplying their estimated energy demand through renewable energies. Only Madrid requires transport in the first period under consideration, with the addition of the Baleares Islands in the second year. When the percentage to be met is raised to 15%, the Communities that need to obtain hydrogen from neighbouring are Madrid, Baleares Islands, Canarias Islands and C. Valenciana. This result suggests that for the Administration to achieve transition to a hydrogen economy, it should promote production of renewable energies in those Communities and set up the infrastructures required for transporting hydrogen to those Communities from nearby regions.

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