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Evaluation of automobiles with alternative fuels utilizing multicriteria techniques☆

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Abstract

This work applies the non-parametric technique of Data Envelopment Analysis (DEA) to conduct a multicriteria comparison of some existing and under development technologies in the automotive sector. The results indicate that some of the technologies under development, such as hydrogen fuel cell vehicles, can be classified as efficient when evaluated in function of environmental and economic criteria, with greater importance being given to the environmental criteria. The article also demonstrates the need to improve the hydrogen-based technology, in comparison with the others, in aspects such as vehicle sale costs and fuel price.

Keywords: DEA; Automotive; Hydrogen; Environment

1. Introduction

At present, approximately 97% of the energy consumed by vehicles worldwide is based on oil, a contaminating, non-renewable and geographically very localized energy resource. Numerous studies sustain that the environmental problems and those of energy dependency produced by this energy model will be even more serious in the future if the current tendency continues. For example, the International Energy Agency estimates that the consumption of petroleum fuels will double between the year 2000 and 2030 if the current trends continue, and that there will also be a similar increase in greenhouse effect gases (GHG) [1]. These factors have led, over the last few years, to efforts being increased at national and international level to develop Alternative Fuel Vehicles (AFVs).

The growing interest in the development of new technologies for the automotive sector based on alternative fuels is demonstrated by the ever-increasing number of studies published over the past two decades that have focused on analyzing the advantages of these types of engines as against the traditional technologies based on fossil fuels. Among these works we can find particular studies on every one of these fuels, comparative analyses of several of them (see, among others [2–4]), analysis of costs [5–7], or of the market opportunities for alternative vehicles [8–10].

The fundamental problem concerning the development of AFVs is the fact that the main benefits derived from their implantation (reduction of energy dependency and of environmental damages) have no direct affect on the private sector, while this sector does bear the highest costs in comparison to traditional technologies. In order to resolve this problem, and enable AFVs to compete in the future with the vehicles based on traditional fuels, the participation of the public sector backing the private sector is required.

There are six traditional barriers that obstruct the appearance of AFVs in the market [11]:

1. High cost of the vehicle.
2. On-board storage difficulties, which limit vehicle autonomy.
3. Guarantee of security in the use of new fuels.
4. Limited number of fuel stations.
5. Fuel cost, especially in terms related to oil.
6. Improvements to traditional technologies that are leading to optimized and cleaner petrol and diesel engines.

Each new technology has to overcome these obstacles, which makes its success in the market very difficult to achieve. Along with the above-mentioned reasons, one has also to consider the fact that the efforts being made nowadays to enhance

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infrastructures are almost exclusively dedicated to traditional technologies.

One of the alternative technologies currently under study is that used in hydrogen-powered vehicles. These vehicles use hydrogen as fuel, either in an internal combustion engine or in a fuel cell. The former is based on the principles of conventional internal combustion engines, and it is, in fact, a slight modification of them. The latter uses hydrogen to produce electricity in the fuel cell and hence to power an electrical engine.

The objective of this work is to conduct a comparative analysis of hydrogen-powered vehicles and the rest of the alternative fuels for automobiles that are currently being developed. To this end, we apply a non-parametric analysis technique, *Data Envelopment Analysis* (DEA). This technique is suitable for solving these types of problems, where each alternative has to be assessed taking different attributes or criteria into account simultaneously and where, furthermore, the importance that must be assigned to each one of them is a priori not known. In this study, each one of the technologies (defined herein as the combination of the type of engine and fuel) is considered as one of the alternatives to the decision problem. Moreover, each one of the aspects considered as being important in order to determine the adequacy of the technologies (economic, technical, and environmental aspects) is a criterion or attribute of the problem.

The application of this technique allows us to obtain, on the one hand, a relative assessment of vehicles based on hydrogen fuel cells as against the rest of the alternatives, while simultaneously considering the values of each technology with regard to each one of the criteria. In addition, the proposed methodology determines, for each alternative, a reference value for each one of the variables taken into consideration. This information allows us to quantify the improvement that has to be made to a technology in each attribute in order to make it the best option.

The rest of the paper is structured as follows. In the next section we describe the DEA methodology we will utilize to assess the different AFVs. Section 3 presents and argues the obtained results. Finally, Section 4 contains the main conclusions.

2. Methodology

The main parameter of this study is the vehicle technology, defined herein as a combination of the type of engine and the fuel utilized. Each technology shall be considered to be one of the alternatives of the decision problem. The main focus of the work is to obtain an evaluation of each alternative while taking all the relevant aspects (fuel consumption, emissions, acceleration, etc.) into consideration simultaneously.

The evaluations that the alternatives would receive with respect to each one of the above aspects taken into consideration individually would be conflictive in the sense that the ordering induced by said evaluations would not coincide. For this reason, multicriteria analysis techniques must be applied in order to obtain a single evaluation of the alternatives, jointly considering their performance in all the criteria that are relevant for the problem. The only multicriteria decision analysis application for the study of alternative vehicles known to the authors of this paper is [12]. This work analyses twelve types of buses using eleven criteria by means of a Delphi analysis and the application of reference point methods.

The multicriteria procedure employed in this paper is Data Envelopment Analysis (DEA). DEA is a non-parametric analysis technique that was originally conceived to analyze the relative efficiency of a set of production units, which from multiple inputs, produce multiple outputs [13]. However, DEA has greatly exceeded the objective for which it was originally conceived and its field of application is currently much extended. In this work, each technology is expressed as a Unit of Assessment (UOA). We express each unit as a UOA instead of as a Decision Making Unit (DMU), which is the term that is traditionally used in DEA terminology, in accordance with the opinion of [14], given that a vehicle of a specific technology does not take any decision.

The fundamental feature of this analysis is the manner in which the different criteria are weighed to obtain a single evaluation of each alternative. Each UOA alternative has been evaluated with respect to different criteria. Among these evaluations, there are criteria according to which "more is better" (such as fuel saving, reduction of emissions, or vehicle autonomy) and assessments in which "less is better" (such as the cost of the vehicle or fuel consumption). The former are considered in this methodology as the outputs from the problem, and the latter as the inputs; on equality of inputs, the units with the higher output are considered to be better. The evaluation each alternative receives is calculated as the ratio between the weighed value of the outputs and the weighed value of the inputs. If we denote by X_{io} the value that the $\mathrm{UOA_o}$ receives with respect to the input i and by Y_{jo} the quantity of output j that corresponds to that alternative, the coefficient associated to the alternative will be equal to

$$\theta_o = \frac{\sum_j w_j Y_{jo}}{\sum_i v_i X_{io}}, \tag{1}$$

where v and w are vectors of weights of inputs and outputs, respectively. The most significant feature of DEA is that it allows each alternative to select its own weighting vectors. In the majority of decision techniques, the weighting vector for the criteria is determined in parallel to the procedure and is based on the preferences of the agents. In DEA, the methodology itself selects weighting vectors to evaluate each alternative, obtaining the weighting vectors that allow the UOA to obtain the most favorable assessment with a set of conditions that are common for all the units. Therefore, the selection of the weights is done in an objective manner and in equality of conditions for all the alternatives.

With this intention, to obtain the assessment of any unit, unit o that we denote by $\mathrm{UOA_o}$, we solve the following non-linear problem,

$$\begin{aligned} \text{Max} \quad & \theta_o = \frac{\sum_j w_j Y_{jo}}{\sum_i v_i X_{io}} \\ \text{s.a.} \quad & \frac{\sum_j w_j Y_{jk}}{\sum_i v_i X_{ik}} \le 1 \qquad \forall k = 1, \dots, M \\ & v_i, w_j > \varepsilon \qquad\qquad \forall i, j \end{aligned} \tag{2}$$

or, alternatively, its linear transformation,

$$\begin{aligned} \text{Max} \quad & \sum_j w_j Y_{j\text{o}} \\ \text{s.a.} \quad & \sum_i v_i X_{i\text{o}} = 1 \\ & \sum_i v_i X_{ik} - \sum_j w_j Y_{jk} \geq 0 \quad \forall k = 1, \ldots, M \\ & v_i, w_j > \varepsilon \qquad\qquad\qquad\quad \forall i, j \end{aligned} \tag{3}$$

where M represents the total number of alternatives and ε is a sufficiently small positive value. In this manner, the above problem is solved for each UOA, maximizing the value associated to the selected unit, with the value of all the units, including the unit subjected to assessment, being constrained to not being greater than one. The above model is referred to in DEA analysis terminology as CCR-I. For a detailed DEA study, see, for example [15,16].

The solution may provide two different types of results. If the value of the coefficient θ, or efficiency score, is equal to one, this means that the alternative assessed can achieve the maximum value permitted and that there are no alternatives that can surpass it (please, note that ties may exist). That is to say, there is a pair of vectors v and w such that no alternative, assessed as a ratio between output and input, can be considered better than. In this event, the unit is called *efficient*.

On the other hand, the result in the optimal could be less than one. In such a case, we say that the unit is inefficient. In this second option, even in the best possible situation, with the vectors of weights that allow the ratio between outputs and inputs to be maximized, there is one or several alternatives that obtain a higher value and which are considered better than the assessed unit. In this second situation, the value of θ can be interpreted as a percentage of efficiency since it represents, approximately, the percentage reduction the unit's inputs should experience, with the output value remaining unaltered, so that the unit becomes efficient. Therefore, the methodology provides a set of values (called benchmarks) the assessed unit must achieve for each one of the criteria, if it wants to become efficient.

As mentioned previously, DEA methodology, as originally conceived, allows freedom in the selection of the weights. Any weight vector that is not negative and that verifies the constraints of the maximization problem is considered acceptable. Flexibility in the selection of weights is one of the most significant features of DEA and, in many cases, the main criticism of this technique. In order to solve this deficiency, models that permit the inclusion of additional information [17] have been developed. By means of a set of additional constraints to the model (3), the possible values of the v and w vectors can be limited so that they reflect the preferences of the decision makers, although this does not eliminate the characteristic flexible choice of weights of this methodology. We will utilize this approach for the purpose of including preferences on the criteria taken into consideration in the model.

3. Results and discussion

The purpose of this section is to obtain a single evaluation for the alternative technologies taken into consideration by applying the DEA CCR-I model, with the inclusion of ordinal variables [18]. The inclusion of these types of variables is justified by the convenience of including criteria in the assessment for which we do not have more precise numerical values than those represented. The data we will use for the study are basically those contained in [3,7]. The first work makes a quite thorough analysis of the main alternative fuels, analyzing 23 different technologies, within the European context. However, while this report does not include a survey of the cost derived from the use of fuel or of the economic assessment of the emissions, this information does appear in [7]. For this reason, we take the 15 alternatives studied in the second aforementioned work as our base.

The technologies assessed include traditional internal combustion engine vehicles (ICEV), hybrid engine vehicles (HEV), where an electric engine coexists with a traditional internal combustion engine, and vehicles with fuel cell power systems (FCV) powered with gasoline, methanol (in both cases by on-board reforming), or hydrogen (produced from different sources). The 15 alternatives we analyze are summarized in Table 1.

In the fuel cell vehicles powered by hydrogen obtained at stationary production plants using natural gas or coal, two possible costs of the fuel are considered. These values are represented in brackets and are expressed in dollars per gasoline gallon equivalent (g.g.e.). The explanation is that, in these cases, the alternatives with a higher fuel cost (units 12 and 14 in Table 1) include CO_2 sequestration (which units 11 and 13 do not include). Therefore, their higher values in fuel cost are compensated by better evaluations with regard to environmental criteria. A more detailed analysis of the alternatives is included in [7].

We assume that all the vehicles are similar as regards aesthetics, performance, safety, etc. As a consequence, the comparison is only made in function of the features derived from the performance of the engine, storage system, and type of fuel. The variables initially taken into consideration for assessment in this study are summarized in Table 2.

The first five criteria represent the inputs of the problem: the vehicles with a lower value are associated with more efficient performances. The last two variables will be considered the outputs from the model and, in equality of conditions in the first five criteria, consumers would prefer a higher value. It is important to note that in the DEA model utilized, CCR-I, the output values are considered as given values. This model will determine the changes needed in the input values so that the inefficient units become efficient units.

When we apply the previous model, with the aforementioned variables, we obtain a result that is not very realistic. Almost all the alternatives assessed turn out to be efficient. This result arises as a consequence of the high number of variables employed (7) in comparison to the number of units to be assessed (15). Therefore, prior to the obtaining of the results, we apply the methodology proposed in [19] for the selection of the most fruitful inputs and outputs for the study. The objective of this procedure is to

Table 1
Alternatives of the study

	Alternative	Features engine	Fuel
1	ICEV SI Gasoline	Internal combustion	Gasoline
2	ICEV SI Adv. Gasoline	Advanced internal combustion	Gasoline
3	ICEV SI H2 (NG)	Advanced internal combustion	Hydrogen
4	HEV SIDI Gasoline	Hybrid	Gasoline
5	HEV CNG	Hybrid	Compressed natural gas
6	HEV SI H2 (NG)	Hybrid	Hydrogen
7	HEV CIDI Diesel	Hybrid	Diesel
8	HEV CIDI FT50	Hybrid	Combination Fischer–Tropsch and diesel
9	FCV Gasoline	Fuel cell	Gasoline
10	FCV Methanol (NG)	Fuel cell	Methanol
11	FCV H2 (NG) (2.21)	Fuel cell	Hydrogen from natural gas
12	FCV H2 (NG) (2.46)	Fuel cell	Hydrogen from natural gas
13	FCV H2 (coal) (2.24)	Fuel cell	Hydrogen from coal
14	FCV H2 (coal) (2.48)	Fuel cell	Hydrogen from coal
15	FCV H2 (wind)	Fuel cell	Hydrogen from wind power

Table 2
Variables taken into consideration

Variable	Description
Purchase cost	Estimate of the retail price of a vehicle (4–5 occupants) with similar services, expressed as an increase over a reference price. The estimate is based on the mass production of the vehicles and does not include the cost derived from the launching of new technologies onto the market [7]
Environmental cost	Assessment of the economic cost of damage to the environment derived from the use of the vehicle, obtained from the emissions for use and from an estimate of the environmental damage per unit of emission. To calculate this, a present value of 10 years, with a 3% discount rate, has been obtained. All the emissions of gases in the complete fuel cycle, from its extraction up to its utilization by the vehicle, are taken into consideration. Moreover, an oil supply insecurity cost [7] is included
Fuel cost	Calculated as the present value (8% discount rate) of the cost derived from driving 19,300 km year^{-1} for 10 years [7]
Acoustic emissions	We include a categorical variable that reflects the acoustic contamination derived from the use of each type of vehicle, in which the lowest value is assigned to the alternative with the best performance. Own elaboration
Energy consumption well to wheel	The estimated energy required for each type of technology, expressed in MJ/100 km [3]. The complete cycle (Well to Wheel) is taken into consideration and the most representative production pathways according to the authors' criteria have been chosen for each type of energy.
Maximum speed	Maximum speed of the vehicle, expressed in km h^{-1} [3]
Acceleration	Vehicle acceleration, expressed as an inverse of the time required to go from 0 to 100 km h^{-1} [3]

identify the variables with the least influence on the determination of the efficiency coefficient of the alternatives, so that their elimination would result in a lower loss of information. In our case, the two outputs turn out to be the variables with the least influence on the efficiency value of the UOAs; that is to say, the discrimination capacity of the speed and acceleration variables of the vehicles is very low and, therefore, these variables are dispensable.

Therefore we, resolve a model known as the pure input model in DEA literature. All the variables are inputs and a single output with a value equal to the unit is included. We assess a set of vehicles that are similar in services, based on their performance as regards cost, emissions and energy consumption. The values that describe the variables finally included in the study are summarized in Table 3.

We incorporate an array of additional constraints in the CCR-I model to ensure that the importance assigned to some environmental aspects of the study, environmental cost and energy consumption, is greater than that of the economic aspects. As mentioned in the introduction, the traditional vehicles have a clear competitive advantage in the economic aspect; for this reason, the introduction of AFVs in the market can only be justified if their environmental advantages are taken into consideration.

Table 4 summarizes the efficiency values for each UOA. In the case of the inefficient units, we also indicate the reductions required for each variable in order to enable the technology to achieve efficient assessment.

Of note is the fact that most of the efficient UOAs are existing technologies or with a certain degree of maturity (units 1–8).

Table 3
Variables included in the model

	Maximum	Minimum	S.D.
Retail price (€)	8,870	2837	1,365.73
Air-pollutant damage cost (€)	14,122	8040	1,5246.28
Fuel cost (€)	3,394	996	753.83
Noise production (categorical)	4	1	1.18
Energy consumption well to wheel (MJ/100km)	309	156	46.07

Table 4
Efficiency values and improvement required

	UOA	Score	Retail price (%)	Air emission damage (%)	Fuel cost (%)	Energy	Noise
1	ICEV SI Gasoline	1.000					
2	ICEV SI Adv. Gasoline	1.000					
3	ICEV SI H2	0.911	0.65	18.81	28.69	44.01	66.67
4	HEV SIDI Gasoline	1.000					
5	HEV CNG	1.000					
6	HEV SI H2	0.904	4.90	15.19	14.59	36.86	66.67
7	HEV CIDI Diesel	1.000					
8	HEV CIDI FT50	1.000					
9	FCV Gasoline	0.996	29.74	35.29	0.00	6.49	50.00
10	FCV Methanol	0.937	10.88	10.70	0.00	35.93	50.00
11	FCV H2 (NG) (2.21)	1.000					
12	FCV H2 (NG) (2.46)	1.000					
13	FCV H2 (coal) (2.24)	0.970	0.00	5.95	0.00	23.11	0.00
14	FCV H2 (coal) (2.48)	0.994	0.00	1.25	0.99	23.11	0.00
15	FCV H2 (wind)	1.000					

Together with these, technologies based on hydrogen fuel cells appear. This is a consequence of their good performance in environmental criteria and in spite of the need for the technology to be matured.

It is interesting to see how, within the FCVs, both the cheapest technology, hydrogen produced from natural gas, and the cleanest technology from an environmental point of view, wind power, are efficient. In the case of units 9 and 10, a lower production cost is compensated by a worse performance in CO_2 emissions as a consequence of the on-board reforming process.

It is important to underline that the variations included in the table are expressed with respect to the reference unit obtained by the model. For each inefficient unit, the model determines a reference unit or benchmark, obtained as a linear combination of efficient units. This reference unit represents the value that the inefficient units must reach in order to be efficient, and they are particular to each UOA. The fact that a unit is classified as efficient means that it may be, but not necessarily, part of the reference value of an inefficient UOA. The efficient units that are not utilized by the model to construct benchmarks are the most "extreme" units, alternatives that achieve efficient assessment due to extreme values in some criterion. The fact that these alternatives are not similar to the rest of the units means that they are not utilized as a reference point for possible improvements to inefficient units.

The variation percentages of the ICEV SI H2 vehicle (internal combustion vehicle that uses hydrogen as fuel), for example, are variations with respect to unit 12, fuel cell vehicles powered by hydrogen produced from natural gas, FCV H2 (NG) (2.46), which is the only unit included in its reference value. Nonetheless, the percentages of the fuel cell vehicles powered by methanol (FCV Methanol) are expressed as a linear combination of the values of units 11 and 12, with a weight of 0.7148 and 0.2852, respectively. In each case, the model selects, as a reference unit, the nearest point of the assessed UOA at the efficiency frontier, comprising all the linear combinations of efficient units.

From the values indicated in Table 4, we can affirm that the units considered as efficient have a better performance than the inefficient units. For each efficient unit, there is at least one weighting vector for the inputs and outputs that ensures that the ratio between weighted output and inputs is not exceeded by any other alternative. Any efficient unit performs better than the inefficient units. In addition, we can establish a ranking for the inefficient units in function of their efficiency score. For example, in the case of units 13 and 14, we can see how the advantage in the environmental damage assessment of the latter compensates the lower fuel cost of unit 13. The fact that additional constraints ensuring greater importance being given to the environmental criteria are included, leads to a higher efficiency coefficient of unit 14. It is important to point out that the null deviation in the retail price does not mean that its performance is efficient with respect to this variable. Firstly, this value must be taken to mean that there are no differences in the retail price with respect to their reference values. Secondly, the values of this variable are compensated by improvements in other criteria as reflected in Table 4.

However, no criterion that allows two efficient units to be compared exists a priori. It cannot be said that one efficient unit is superior to another given that each one obtains its efficiency score using its own weighting vector, subject to certain common conditions, as mentioned previously, and with a different combination of values. For example, an alternative may be efficient due to good values in retail price and fuel cost, in such a way that it compensates bad performance in environmental variables. This is the case with the gasoline vehicles (units 1 and 2). On the other hand, high values in the retail price and the cost of fuel can be compensated by significant advantages in energy consumption (units 11 and 12) or in relation to environmental cost, as in the case of the natural gas vehicles (units 5, 11 and 12).

To establish a full ranking of the UOAs, including the efficient units, several possible proposals based on the DEA methodology are available. One of the best known is called cross-efficiency matrix, developed in [20]. This methodology consists of assessing each alternative, not only with its own weights, but also with the vectors of the rest of the units. The possible multiplicity in the optimal vectors is solved by taking, for each alternative, the vector that maximizes its own efficiency coefficient and, as a sec-

Table 5
Cross-efficiency matrix

UOA's weighting vector																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Average
UOA's score																
1	1.000	0.805	0.812	0.915	0.787	0.813	0.738	0.804	0.607	0.767	0.760	0.803	0.765	0.824	0.891	0.806
2	1.000	1.000	0.971	1.000	1.000	0.970	0.898	1.000	0.798	0.961	0.960	1.000	0.961	1.000	1.000	0.968
3	0.733	0.898	0.911	0.724	0.890	0.911	0.693	0.897	0.519	0.829	0.823	0.897	0.827	0.909	0.742	0.813
4	0.963	0.973	0.950	1.000	0.970	0.950	0.951	0.973	0.917	0.960	0.959	0.973	0.960	0.962	0.996	0.964
5	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.898	1.000	1.000	1.000	1.000	1.000	1.000	0.993
6	0.760	0.896	0.904	0.765	0.887	0.904	0.743	0.895	0.589	0.846	0.840	0.894	0.844	0.899	0.779	0.830
7	0.961	0.933	0.930	0.962	0.925	0.931	1.000	0.933	1.000	0.960	0.959	0.932	0.960	0.924	0.953	0.951
8	0.950	1.000	0.975	1.000	1.000	0.974	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.983	1.000	0.992
9	0.810	0.761	0.775	0.832	0.740	0.776	0.871	0.759	0.996	0.791	0.786	0.758	0.790	0.749	0.817	0.801
10	0.789	0.923	0.927	0.765	0.915	0.927	0.842	0.922	0.775	0.937	0.935	0.922	0.936	0.917	0.781	0.881
11	0.991	0.989	0.986	0.993	0.987	0.986	1.000	0.989	1.000	1.000	1.000	0.989	1.000	0.985	0.997	0.993
12	0.992	1.000	1.000	0.993	1.000	1.000	0.986	1.000	0.944	1.000	1.000	1.000	1.000	1.000	1.000	0.994
13	0.898	0.960	0.959	0.876	0.955	0.959	0.913	0.960	0.871	0.970	0.969	0.959	0.970	0.957	0.887	0.938
14	0.899	0.993	0.994	0.877	0.993	0.994	0.912	0.993	0.829	0.993	0.992	0.993	0.993	0.994	0.893	0.956
15	1.000	0.938	0.952	1.000	0.932	0.953	0.892	0.937	0.778	0.903	0.900	0.937	0.902	0.950	1.000	0.932

ondary objective, maximizes that of the rest of the alternatives. This is known in literature as *benevolent evaluation*.

In this way, each unit is assessed 15 times given that this is the number of units included in the study. The average of these efficiency scores can be taken as the average efficiency indicator as it has been obtained with the weights imposed by all the alternatives. The values obtained are summarized in Table 5. The assessments of the UOAs appear in each row. The columns refer to the unit whose optimal weighting vector has been utilized for the assessment.

Among the above results we wish to emphasize the overall bad scoring achieved by UOA 1, a traditional gasoline vehicle. This result can be explained by the constraints we have added in order to obtain the efficiency scores. As we have included a set of additional constraints that give greater importance to the environmental aspects, in the assessment of the units, when this unit UOA 1 is assessed with the optimal weights of other units, its advantage in costs cannot be exploited, and its evaluation is medium-low.

Units 3 and 6 can be seen as transition technologies. The low evaluations received indicate their poorer performance in environmental terms, compared to FCVs, while they also are at a cost disadvantage in relation to the traditional technologies. The expected improvements of the FCVs in relation to retail price and cost of fuel would place these technologies above the previous two.

In the case of unit 9, its poor evaluation in terms of average efficiency is a reflection of a complex technology, as yet not very developed and not especially clean in terms of CO_2 emissions. UOA 10 is in a similar position. Both cases refer to fuel cell vehicles with on-board reforming.

Units 11 and 12, FCVs with hydrogen produced from natural gas, are outstanding for the opposite reason. The good general performance in all environmental aspects of these units together with the aforementioned constraints in weights, justify their good average evaluation in the fifteen assessments. In spite of it being a fossil resource, it is relatively clean and the technologies employed have an acceptable degree of maturity. This same reasoning can be applied to natural gas hybrid vehicles (unit 5). In addition, in this case there are advantages over the former in retail price and fuel cost.

4. Conclusions

In this work we have conducted a comparative study of the main alternative fuels for the automotive sector by applying Data Envelopment Analysis. The use of this technique allows quantification of the differences that exist between the different technologies, shows what should be the improvement in each one of the assessment criteria to allow a technology to become an efficient alternative, and ranks the alternatives.

The results indicate that, with the values provided by [3,7], some of these technologies can be classified as efficient when assessed in function of environmental and economic criteria, with the environmental criteria outweighing the economic criteria.

The superiority of the technologies that are currently implemented, such as ICE gasoline engines, is based fundamentally on their better performance in the economic criteria, vehicle retail price and fuel cost. The existing alternatives are classified as efficient when they are assessed with the vectors of weights that are most favorable to the alternative; that is to say, with the vector obtained as the solution from the DEA model. However, their assessment worsens notably when we calculate the cross-efficiency values, given that these alternatives are then assessed with the weighting vectors of the rest of the units as well, where greater importance is given to the environmental aspects. In this case, the traditional internal combustion technology achieves an evaluation that is below that of some of the FCVs.

Moreover, the better performance from an economic point of view of the traditional vehicles is due basically to the large investment made in research and development on these types of vehicles throughout the years. These vehicles are at a very advanced stage of development and are, therefore, not easily comparable to vehicles that are at the early stages of development where economic profitability is lower. For this reason, we have conducted the study putting greater emphasis on environmental aspects.

In relation to the hydrogen-based automotive technologies, these also perform well if we compare them to the other technologies that are currently under development. Within the hydrogen-based technologies, only the fuel cell vehicles powered by hydrogen are efficient due to their better values under the environmental damage and energy consumption criteria. This technology achieves this evaluation in spite of it having a higher retail price, derived from its lesser development, with respect to the hybrid and internal combustion vehicles. It is interesting to note, within the fuel cell technology, how production from coal does not appear as a good option, in contrast to the production from natural gas or wind.

Therefore, this work shows how some automotive technologies under development (such as those based on hydrogen) can be cataloged as efficient depending on society's preferences for the criteria (environmental or economic) taken into consideration. If society's preferences for the environmental criteria were higher than for the economic, then some AFVs could currently be a solid alternative to traditional fuel vehicles, provided the public sector were to establish the mechanisms required to transfer these preferences to the market.

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