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PLANNING THE ROLL-OUT OF HYDROGEN FUELING INFRASTRUCTURE FOR TRANSPORTATION: A CASE STUDY IN SPAIN, ANDALUSIA AND SEVILLE

A dissertation submitted in partial satisfaction of the requirements to obtain the
Ph.D. European Graduate Degree
by
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A Patricia, mi mujer,
y a Javier Jr., que conducirá
(D.M.) un coche de hidrógeno

-"Oui, mes amis, je crois que l'eau sera un jour employée comme combustible, que l'hydrogène et l'oxygène, qui la constituent, utilisés isolément ou simultanément, fourniront une source de chaleur et de lumière inépuisables..." Cyrus Smith

Jules Verne, L'Île Mystèrieuse, 1875

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INTRODUCCIÓN

El actual modelo energético del sector transporte, basado fundamentalmente en el uso de combustibles fósiles, presenta una serie de problemas fundamentales que afectan a su propia supervivencia:

- la presión que suponen los problemas medioambientales asociados a la producción, transporte y uso de esos combustibles,
- el incremento de la demanda energética,
- y la necesidad de los países de mejorar la seguridad energética, reduciendo la dependencia de los recursos energéticos extranjeros.

Todo ello, está llevando a la búsqueda de modelos energéticos basados en combustibles alternativos. Algunos de estos combustibles alternativos son producidos domésticamente; otros son obtenidos desde fuentes renovables. En muchos casos, son menos contaminantes que los combustibles fósiles. Pero, por otra parte, a pesar de esas ventajas, la penetración en el mercado de los vehículos propulsados por tales combustibles ha sido lenta en los últimos años, debido a que las prestaciones de los mismos (en términos de autonomía, velocidad, tiempo de repostaje, aceleración, etc.) han sido generalmente menores que las de los vehículos de combustibles tradicionales, y porque su coste (tanto del vehículo como del propio combustible) ha sido mayor.

Recientemente, la Unión Europea (UE), a través de la Directiva 2014/94/EU sobre el despliegue de infraestructura de combustibles alternativos, de 22 de octubre de 2014, ha apostado por el desarrollo de una serie de combustibles alternativos, tales como el gas natural, la electricidad o el hidrógeno. Asimismo, la citada Directiva reconoce como uno de los principales obstáculos para el desarrollo de estos combustibles la ausencia de una adecuada infraestructura de abastecimiento. En esta línea, propone a los estados miembros de la UE que establezcan una serie de medidas y estrategias orientadas a favorecer el desarrollo y despliegue de esta infraestructura, de modo que su ausencia no sea un obstáculo para el uso de estos combustibles.

A la hora de afrontar estas estrategias, está claro que los diferentes gobiernos y organismos intentan encontrar el modo de que el despliegue de la infraestructura permita ofrecer la máxima cobertura con la menor inversión posible, o, dicho de otro modo, que el despliegue se lleve a cabo de un modo eficiente. Este es, precisamente, el tema que aborda la presente Tesis Doctoral.

De entre los diferentes combustibles alternativos señalados por la Directiva, esta Tesis Doctoral se centra en el uso del hidrógeno como combustible alternativo para el transporte. El motivo de ello es que este gas se perfila como una de las alternativas futuras mejores a los combustibles tradicionales, ya que:

- puede ser producido localmente, y a partir de fuentes renovables,
- su uso en vehículos produce, únicamente, agua como residuo,
- el precio puede ser competitivo con la gasolina o el diésel, y
- los vehículos de hidrógeno presentan unas prestaciones similares o superiores a los actualmente empleados.

De hecho, los principales fabricantes de vehículos se están centrando en este combustible; valgan, como ejemplo, los vehículos de Toyota (Mirai) o Hyundai (ix35 FuelCell), que se producen en serie en la actualidad y se comercializan en diferentes países. Estos vehículos, al igual que la inmensa mayoría de vehículos de hidrógeno, son vehículos eléctricos que emplean una pila de combustible ("fuel cell", en inglés), para transformar hidrógeno (de un depósito) en agua y electricidad, al combinarlo con el oxígeno del aire. Es decir, son vehículos eléctricos, pero dotados de ventajas adicionales a los que emplean baterías: un tiempo de repostado en el entorno de los tres minutos, una autonomía de más de 500 km y un habitáculo y confort completamente equiparables a los vehículos convencionales.

Hay que destacar que, precisamente, los fabricantes de vehículos de hidrógeno señalaron ya, en 2009, la necesidad de una infraestructura de suministro de hidrógeno como combustible que permitiese la comercialización masiva de estos vehículos. Así, según Daimler, Ford, GM-Opel, Honda, Hyundai-Kia, Renault-Nissan y Toyota, es imprescindible para la penetración de estos vehículos que su comercialización esté alineada con el despliegue de una infraestructura formada por estaciones de servicio de hidrógeno (ESH) que sean accesibles al público, estén estandarizadas, bien localizadas y dispensen este combustible a un precio competitivo.

Diferentes países y regiones han sido conscientes de la importancia de este combustible alternativo, y han comenzado ya a definir su estrategia de despliegue de infraestructura para favorecer el empleo del hidrógeno como combustible en el sector transporte. Así, en el ámbito internacional, destacan los casos de Japón y EEUU.

La autopista del hidrógeno ("hydrogen highway") japonesa es una red de ESH a lo largo de los principales nodos de carreteras del país. Los objetivos establecidos son implementar 100 estaciones de servicio en 2015 en las cuatro principales ciudades niponas (incluyendo Tokio), para llegar a la comercialización a escala global en 2030 (Figura 0.1).

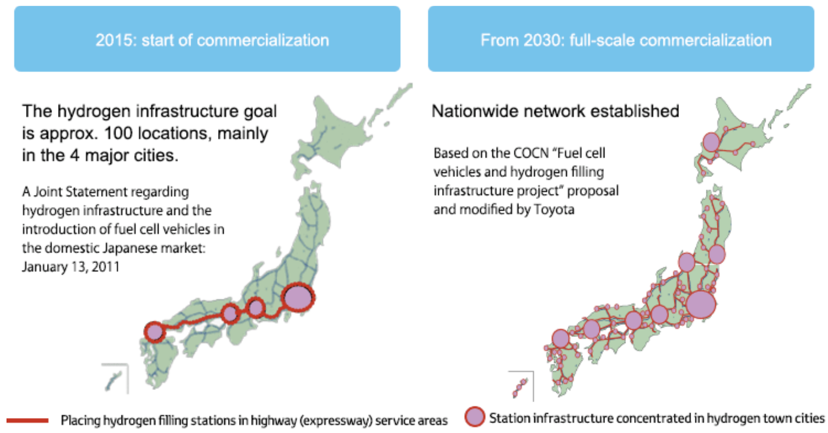

Figura 0.1.- Hoja de ruta de estaciones de servicio en Japón
(Fuente: http://www.meti.go.jp/)

En EEUU, merece la pena destacar la California Fuel Cell Partnership (CaFCP, http://cafcp.org/), lanzada en 1999 por la Comisión de Energía del estado de California (California Energy Commission) y el California Air Resources Board. En el año 2012, CaFCP estableció una hoja de ruta (Figura 0.2) para implementar ESH de manera que estuvieran disponibles cuando llegara al mercado el vehículo de hidrógeno. La localización de dicha infraestructura se estableció en base a criterios favorables al consumidor, teniendo en cuenta la ubicación de gasolineras ya existentes (Figura 0.3), así como el lugar en el que el consumidor vive y trabaja, o pasa su tiempo libre. De esta forma se establecieron cinco clústeres geográficos en el estado de California, así como una serie de conectores y ciudades destino, configurando así una red regional (Figura 0.4).

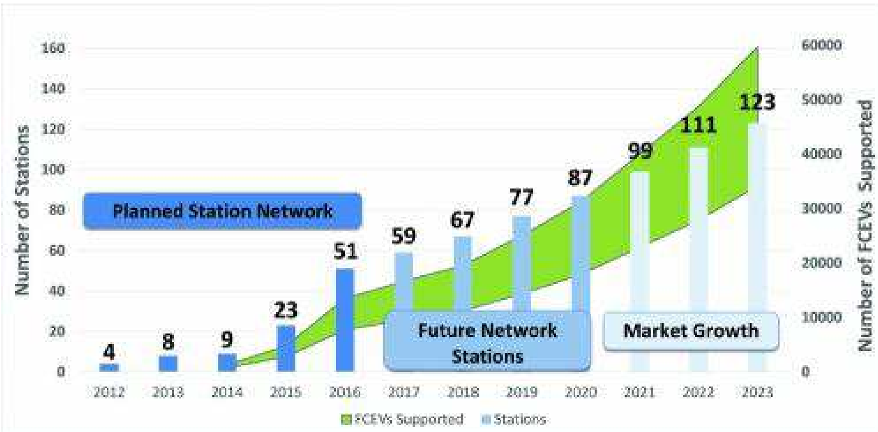

Figura 0.2.- Estrategia de despliegue de ESH en California
(Fuente: http://cafcp.org/)

Figura 0.3.- Estación de servicio en Newport Beach, California

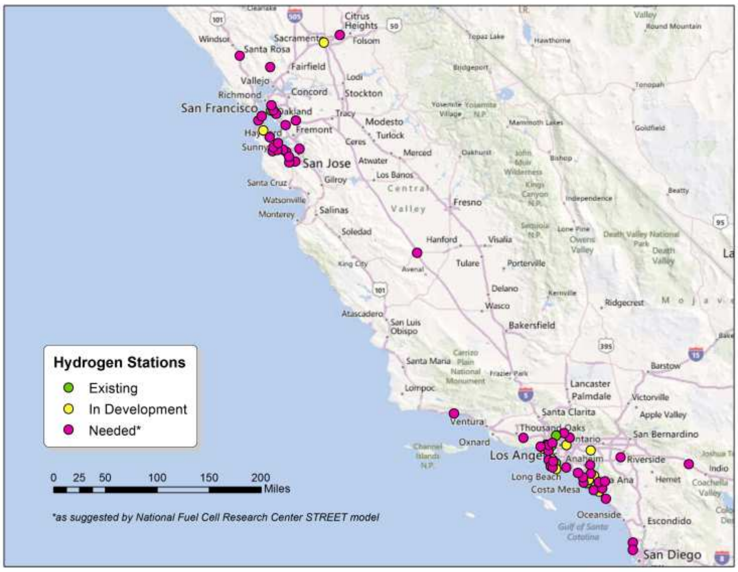

Figura 0.4.- Estaciones de servicio de hidrógeno en California
(Fuente: http://cafcp.org/)

En el ámbito europeo, destacan las iniciativas de Escandinavia, Reino Unido y Alemania. En los Países Escandinavos, aglutinando las iniciativas de Suecia, Noruega y Dinamarca (Hydrogen Sweden http://www.hydrogensweden.com/, HyNor http://hynor.no/en/ y Hydrogen Link http://www.hydrogenlink.net/eng/, respectivamente), se encuentra la plataforma Scandinavian Hydrogen Highway Partnership (SHHP; http://www.scandinavianhydrogen.org/). Se trata de una red transnacional de colaboración en el desarrollo de infraestructura de suministro de hidrógeno, produciéndolo a partir de diferentes fuentes locales de origen renovable. Esta iniciativa cuenta con financiación público-privada, así como con esquemas de exención impositiva. La fortaleza de esta red viene demostrada por el acuerdo firmado entre varias firmas automovilísticas (Toyota, Nissan, Honda y Hyundai), en octubre de 2012, para acelerar la introducción en el mercado de los países nórdicos (incluyendo también a Islandia) de vehículos de pila de combustible, a partir de 2015. Los objetivos previstos por la red escandinava para dicho año son 15 estaciones de servicio y 30 más de carácter satélite, así como una gran flota de vehículos integrada por 100 autobuses, 500 automóviles y 500 vehículos especiales (vehículos industriales, etc.).

En el caso del Reino Unido, y bajo el paraguas denominado UK H2 Mobility (http://www.ukh2mobility.co.uk/), se ha programado el establecimiento de alrededor de 65 ESH hasta 2020, de más de 300 en 2025 y de unas 1.150 para 2030. La planificación del despliegue se ha realizado atendiendo a los niveles de población, ingresos y densidades de tráfico existentes en las diferentes áreas del Reino Unido. Esta estrategia de despliegue aparece representada en la Figura 0.5.

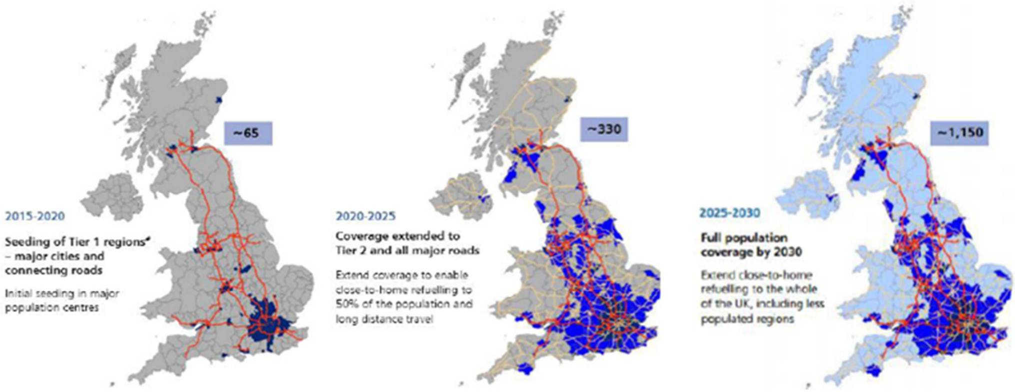

Figura 0.5.- Estrategia de despliegue de ESH en el Reino Unido
(Fuente: http://www.ukh2mobility.co.uk/)

En el caso de Alemania, y bajo la iniciativa NOW 2013 (http://www.now-gmbh.de/), 400 ESH serán puestas en servicio para 2023, 100 de las cuales entrarán en servicio en 2017. El despliegue en este caso empezará a partir de la infraestructura existente y gradualmente se expandirá hacia las zonas con una menor demanda, dando cobertura a la mayor parte de Alemania para 2023. Se han planificado 10 ESH para cada una de las 6 áreas metropolitanas representadas en la Figura 0.6, y las estaciones situadas a lo largo de la red nacional de carreteras y los corredores de hidrógeno servirán para posibilitar los desplazamientos a lo largo de Alemania y la conexión con los países limítrofes.

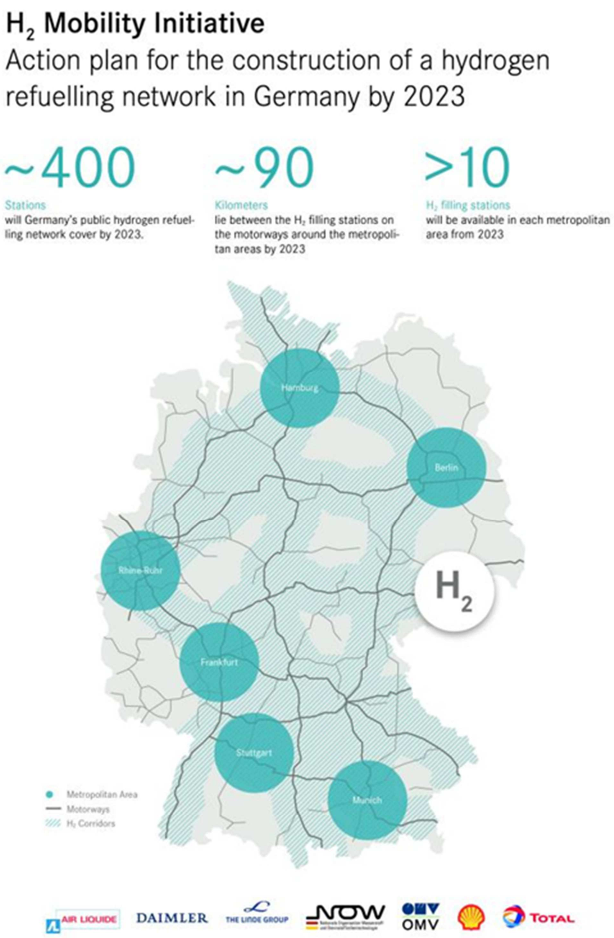

Figura 0.6.- Estrategia de despliegue de ESH en Alemania
(Fuente: http://www.now-gmbh.de/)

En 2015 se ha lanzado una coalición que aúna esfuerzos entre las tres iniciativas europeas referenciadas (Scandinavian Hydrogen Highway Partnership, UK H2 Mobility y H2 Mobility Deutschland), así como con Mobilité Hydrogène France, y que se ha venido a denominar Hydrogen Mobility Europe Project (H2ME, http://h2me.eu/). Bajo esta coalición se van a implementar y poner en uso 200 vehículos de hidrógeno, 125 furgonetas eléctricas (con pila de combustible para extender su autonomía) y 29 nuevas estaciones de servicio, en 10 países diferentes: Alemania, Austria, Bélgica, Dinamarca, Francia, Islandia, Noruega, Países Bajos, Reino Unido y Suecia, para el año 2019.

En general, como se ha visto, en Europa, las estrategias de despliegue han sido definidas basándose en dos ejes fundamentales: ciudades relevantes e interconexiones (o, al menos, garantizando que las ciudades están lo suficientemente próximas como para que estas interconexiones no sean necesarias). No obstante, no se ha sistematizado en profundidad cómo llevar a cabo estrategias de despliegue eficientes para diferentes escalas regionales y escenarios temporales.

El objetivo global de la presente Tesis Doctoral es desarrollar métodos que permitan diseñar estrategias óptimas de despliegue de infraestructuras de respostaje de hidrógeno para automoción para diferentes contextos. Este objetivo general lleva a la necesidad de adoptar una aproximación multidisciplinar integrando diferentes enfoques.

Para la planificación del despliegue de la infraestructura de ESH, es necesario definir previamente algún concepto de idoneidad que permita la identificación de las zonas más adecuadas para el establecimiento de las estaciones de servicio. Este concepto de idoneidad posee dos características fundamentales. En primer lugar, no es estático (en la medida en que depende de la fase del proceso de despliegue que se esté considerando); ello conlleva que áreas consideradas como adecuadas en las primeras fases pueden no serlo en las siguientes. En segundo lugar, la idoneidad viene determinada por diversos criterios.

Para la identificación de las zonas "más idóneas" existen dos aproximaciones fundamentales: métodos basados en modelos de optimización, por un lado, y aproximaciones basadas en el empleo de sistemas de información geográfica, por otro. La primera de las aproximaciones hace uso de modelos matemáticos de optimización para lograr un diseño eficiente de la infraestructura atendiendo a uno o más criterios. La segunda aproximación, por su parte, se centra en la dimensión espacial para situar las estaciones de repostaje de hidrógeno; la localización de estas estaciones y las redes son identificadas mediante el uso de múltiples criterios espaciales.

En esta Tesis Doctoral se utilizan estas aproximaciones para efectuar propuestas de estrategias de despliegue para diferentes ámbitos territoriales: país, región y ciudad. De cara a evaluar los métodos que se proponen, se llevan a cabo aplicaciones prácticas, tomando como unidad de análisis los casos de España, Andalucía y Sevilla (provincia y municipio), respectivamente. Hay que señalar que, por otra parte, no existen en estos momentos propuestas de despliegue de infraestructura de hidrógeno para el territorio español, lo que hace doblemente interesante el objeto de este trabajo.

Así, en el Capítulo 1, se realiza una planificación óptima del número y localización de ESH que permiten abastecer la Comunidad Autónoma de Andalucía, atendiendo a una serie de criterios de oferta, demanda y de carácter medioambiental. Estos criterios se seleccionan mediante revisiones bibliográficas y reuniones informales con expertos. Posteriormente, estos criterios se agregan mediante el empleo del denominado Proceso Analítico Jerarquizado y entrevistas realizadas a expertos para obtener una puntuación que recogiese la idoneidad de cada municipio. Estas puntuaciones permiten identificar zonas de expansión preferente en Andalucía para una fase inicial del despliegue. Finalmente, las puntuaciones de idoneidad de cada municipio se emplean como input en un modelo de optimización, con el propósito de dar cobertura a toda Andalucía, imponiendo como única restricción que los municipios elegidos no se encuentren a menos de 25 km de distancia.

En el Capítulo 2, partiendo de los resultados del capítulo anterior, se diseña una estrategia inicial de despliegue para el caso de la Comunidad Autónoma Andaluza, mediante una aproximación basada en nodos principales, agrupaciones (o “clusters”) y nodos de interconexión. Un nodo principal es un área (municipio) seleccionada para localizar ESH debido a su idoneidad. Un “cluster” es un grupo de nodos principales que están todos ellos suficientemente próximos entre sí, y que conjuntamente agrupan al menos un porcentaje predefinido de población. Un nodo de interconexión es un área (municipio) que es seleccionada dentro de un “cluster” para situar ESH cuando los nodos principales distan en más de una distancia predefinida; su objetivo es “conectar” los nodos principales dentro de un “cluster”, reduciendo la distancia que el conductor tendría que recorrer para repostar el automóvil, mejorando así la percepción de la disponibilidad del combustible. A partir de estos conceptos, en este capítulo se define una estrategia de despliegue, estableciendo la localización, número y tamaño de las ESH en Andalucía, para diferentes horizontes temporales, así como un cálculo de la inversión en infraestructura necesaria para realizar este despliegue, a partir de los costes estimados de los diferentes tipos de ESH, en cada horizonte temporal considerado.

En los Capítulos 3 y 4 se desarrollan y aplican a España y a la provincia de Sevilla, respectivamente, procedimientos de selección de zonas (municipios) idóneas, a partir de múltiples criterios basados en el análisis envolvente de datos. El análisis envolvente de datos es una técnica no paramétrica, concebida originalmente para la medición de la eficiencia de un conjunto de unidades que obtienen múltiples outputs a partir de múltiples inputs. En la actualidad, la aplicación de los modelos de análisis envolvente de datos ha sobrepasado ampliamente sus objetivos iniciales, generando un gran número de modelos y procedimientos, todos caracterizados por una selección endógena de los pesos; el vector de ponderaciones es determinado como una variable del problema y no externamente fijado por los decisores. El propósito de estos dos capítulos es, por tanto, identificar las zonas más idóneas para el establecimiento de ESH, reduciendo la subjetividad que puede existir al agregar los diferentes criterios que caracterizan los diferentes municipios.

El capítulo 5 se centra en la planificación de la infraestructura dentro de un área metropolitana. Mientras en los capítulos anteriores la unidad mínima de análisis considerada era el municipio (7.959 en la España peninsular, de 770 en Andalucía y de 104 en la provincia de Sevilla), y el propósito era planificar a nivel intermunicipal el despliegue de infraestructura según la idoneidad de los municipios para el establecimiento de ESH y/o su capacidad de interconexión, en este capítulo la idea es realizar una planificación intramunicipal para el caso de aquellos municipios especialmente relevantes.

Con esta finalidad, en este último capítulo, se propone un modelo de optimización para planificar el despliegue de ESH en un municipio (ciudad). Este modelo considera dos criterios. El primer criterio consiste en maximizar el nivel de accesibilidad a toda el área metropolitana, cuantificándose este nivel de accesibilidad como la distancia media desde los hogares de los habitantes de la ciudad a la ESH más cercana. El segundo criterio consiste en maximizar el tráfico cubierto por las ESH. Este modelo se desarrolla bajo la hipótesis de que no existe información sobre el par origen-destino de los viajes realizados por los ciudadanos; es decir, las denominadas matrices de origen y destino no están disponibles para la ciudad considerada. La adopción de esta hipótesis se justifica por el hecho de que, en el caso de España, dichas matrices no existen para la gran mayoría de las ciudades.

Este modelo se aplica al municipio (ciudad) de Sevilla, una ciudad del sur de España, con una extensión de 140 km^2 y una población de 700.000 habitantes. Para este caso, se emplean, además, los resultados de una encuesta realizada a más de 200 conductores sevillanos, acerca de su comportamiento en el repostaje, su predisposición al empleo de vehículos con combustibles alternativos y sus requisitos mínimos (respecto al número mínimo de estaciones y a la distancia máxima que habría que recorrer para repostar) a la hora de establecer una red de estaciones de suministro de combustibles alternativos. Toda esta información sirve para recomendar soluciones concretas del modelo, dentro del amplio conjunto de soluciones no-dominadas.

CHAPTER ONE

USING AHP AND BINARY INTEGER PROGRAMMING TO OPTIMIZE THE INITIAL DISTRIBUTION OF HYDROGEN INFRASTRUCTURE IN ANDALUSIA

Abstract

The use of vehicles powered by hydrogen from renewable sources can be a viable alternative for Andalusia, given its accessibility to renewable energies and the problems of energy dependence and pollution resulting from the current energy model. However, the introduction of this type of technology requires an initial infrastructure that solves the classical chicken and egg problem. Given that hydrogen fueling infrastructure will require significant initial capital investment, it is reasonable to assume that a possible strategy of introduction could be the establishment of a station network that is sparse to avoid redundancy and therefore minimize costs. In this chapter, Analytic Hierarchy Process is utilized to rank, on the basis of several supply, demand and environmental criteria, the more than 750 municipalities of Andalusia, according to their suitability for the establishment of hydrogen fueling stations. Subsequently, we incorporate these results into an optimization problem, to achieve optimal planning of the number and location of hydrogen fueling stations, to provide coverage for the region.

1.1. Introduction

The hydrogen economy is regarded, at present, as an alternative to the existing energy paradigm: a new scheme in which, by utilizing local resources, fuel for transportation can be produced from different sources, and can also be distributed and stored safely [I.1]. Hence, the balance of payments improves, the strong dependence on fossil fuel energy diminishes, and the harmful emissions from the transportation sector decline.

Moreover, if the hydrogen originates from renewable energy sources, then the step towards its use becomes a step towards the sustainability and the reduction of greenhouse gas emissions.

However, some social, environmental and territorial conditions are required to enable the shift towards sustainable hydrogen in a specific region. And, given its specific assets, Andalusia could be one of these regions.

Andalusia, an 87,597 km^2 region in the south of Spain, currently avails of an energy model characterized by high dependence on energy imports from abroad, with more than 90% of primary energy consumption being from imports. From 2000 to 2008, the self-sufficiency level was around 5-11% [I.2].

Over that period, energy consumption increased 28.6% [I.2]. This increase in demand for energy is a consequence of, among others:

- demographic growth,
- the shift towards more demanding energy consumption models, and
- the increase in demand for energy from the transportation sector, where there was a significant increase in mobility, mainly of privately-owned vehicles. As regards the latter, there were 5,261,870 vehicles in Andalusia in 2008, which represented a 2.45% increase on the previous year [I.3]. In 2008, the transportation sector was responsible for 36.4% of total consumption [I.2].

Furthermore, in the energy consumption structure of Andalusia there is a predominance of energy sources based of fossil fuels, especially oil and natural gas. In 2008, the two aforementioned energy sources represented around 82% of primary energy consumption in Andalusia [I.2]. Even though a sharper increase in natural gas energy consumption is to be seen in the later years in relation to fossil fuels, oil continues to hold the upper hand. As regards renewable energies, these have been increasing gradually in the later years, although they continue to play a minor role in meeting the global demand for energy (around 4-8% of total consumption from 2000 to 2008).

Given this situation, the Andalusia Sustainable Energy Plan 2007-2013 (PASENER) [I.4] suggests four strategic objectives: (1) to prioritize the use of renewable energies, (2) to involve society in a new energy culture, (3) to contribute to balanced territorial development, and (4) to promote the business sector in the field of energy technologies. Focusing on objectives (1) and (3), the Plan aims “To prioritize the use of renewable sources to increase energy self-sufficiency of the Andalusia population, protection of the environment and implementation of a distributed energy system”, as well as “To contribute to balanced territorial development and economic growth through a system of energy infrastructure that assures a secure, stable, diversified, efficient and quality service to all Andalusians, consistent and adapted to the territorial model established in the Territorial Development Plan for Andalusia”. The Plan also indicates that these objectives are “designed to evaluate the situation in Andalusia regarding renewable energies, energy saving and CO_2 emissions, which define the sustainable energy route the Plan pursues”.

In response to these strategic objectives, this chapter aims to plan the development of an energy model based on the use, in the transportation sector, of hydrogen produced from renewable sources accessible in Andalusia. This model may be seen as a means to mitigate the energy dependence of Andalusia, further the use of renewable energies and the reduction of CO_2 emissions. This chapter contributes to the study of the real possibilities of development, in Andalusia, of an energy vector such as renewable hydrogen, which appears to be emerging, in all aspects, as an efficient, sustainable, reliable and safe means to solve the energy problems in the region.

However, one of the major obstacles to the development of this alternative energy model in Andalusia is the so-called “the chicken and egg dilemma” [I.5-7]:

1. Users will not purchase a vehicle that uses hydrogen as fuel until they can refuel with a minimum of comfort, that is to say, until a basic infrastructure exists.
2. Car manufacturers will not produce these vehicles until there is a demand for them.
3. No company will deploy hydrogen fueling stations without having a minimum of potential customers.

Therefore, to kick off the transition of the market in Andalusia towards hydrogen vehicles, planning of the initial development of the infrastructure that allow the resolving of this problem is required.

In this initiation process, we can distinguish two stages. In a first stage, the objective would be to establish hydrogen fueling stations to supply early-adopters. It may be assumed that these early-adopters will be located throughout the territory or, conversely, that there are regions which by their nature will tend to concentrate a high number of potential purchasers of fuel cell vehicles (FCV). Thus, in this first stage, some regions would be left out of the process. In a second stage, the objective would be to establish hydrogen fueling stations to supply a higher proportion of the population.

Most existing optimal station placement studies focus mainly on providing adequate coverage for all residents [I.8]. This concept of optimality is too restricted because it omits other aspects that could give rise to prioritizing some regions over others [I.7].

Two groups can be distinguished in the literature on infrastructure planning. On the one hand, the papers intended solely to determine the minimum number of hydrogen fueling stations required to allow hydrogen vehicles to get a foothold in the market. In this group, we can mention the works by [I.6, I.9, I.10].

In a second group, we can include the articles focused on optimally planning the geographic location of hydrogen fueling stations. Most of these studies use existing gas stations to determine the potential locations and utilize their accessibility (normally measured as the average travel time each resident would need to reach a hydrogen fueling station) as optimization criterion to locate the hydrogen fueling stations [I.11, I.12, I.13]. On the other hand, the CaFCP [I.14] identifies a number of priority communities in California for a first implementation phase through interviews with auto-makers and transit agencies. These areas were subsequently used by [I.8, I.15] to identify a network of stations that would minimize the average travel time (local and regional). Kuby et al. [I.16] divide the study area into zones, represent each zone by a single origin-destination point and use flow volumes that can be refueled as placement criterion. Finally, Melendez and Milbrandt [I.17, I.18] use Geographic Information System (GIS) to delineate urban and inter-regional areas that satisfy a series of criteria (basically, demand) and, thereby determine the possible locations for a number of previously defined hydrogen fueling stations.

In this regard, this chapter aims to:

- Prioritize Andalusia’s 770 municipalities considering their suitability for FCV penetration. This ranking of Andalusia municipalities will provide information for decision-makers on the potential municipalities that would have to be served in a first stage of the initiation process.
- Determine a minimum number of hydrogen fueling stations in Andalusia that shatter the chicken and egg problem, that is to say, the number of stations required to give potential hydrogen vehicle purchasers the idea that there are sufficient fueling sites [I.5].
- Locate/position the fueling stations optimally throughout Andalusia.

- Conduct all this planning in accordance with the criteria established in the PASENER 2007-2013 [I.4] in relation to CO_2 emission reductions, diversification of energy sources, and balanced territorial development of Andalusia.

The importance of planning for correct market transition has been stressed by several authors [I.7, I.11, I.19 – I.22]. For example, Nicholas et al. [I.11] showed that inappropriate location of stations greatly increases the number of stations required (and thus the cost too); Schwoon [I.7] demonstrated that a carefully planned initial network can kick-start a transition, but that poor planning can lead to failure of transition (resulting in excessively high costs).

The structure of this chapter is as follows. In Section 1.2, we describe the criteria taken into consideration to locate the hydrogen fueling stations. In Section 1.3, we prioritize Andalusia's municipalities in response to the aforementioned criteria. In Section 1.4, we plan the network of stations that allows coverage of all Andalusia. And, lastly, in the final Section, we provide the main conclusions and suggest future tasks.

1.2. Criteria used to site fueling stations

This chapter aims to optimally plan the development of hydrogen infrastructure in Andalusia to facilitate market transition. To this end, we have developed a placement proposal for hydrogen fueling stations that includes:

- consideration of the municipality[1] as a minimum territorial unit, and
- identification of some criteria that allow their evaluation in terms of their suitability for a hydrogen fueling station.

Thus, we consider the concept of optimality in a broad sense, taking different criteria into account when developing the planning process.

The adoption of the municipality as a minimum territorial unit divides Andalusia up into a mesh of 770 municipalities[2], each with its associated territory. This division process provides us with sufficient discretization, favors the local economies, and identifies the political authorities that must make the decisions.

[1] Municipality is a portion of territory in a single jurisdictional area under the authority of a town council.
[2] Number of existing municipalities in Andalusia in 2009.

Each municipality was characterized on the basis of a number of criteria:

1. Demand Criteria.

   With these criteria we aim to identify the municipalities where there may be more likely FCV buyers. We thereby facilitate access to hydrogen fueling stations in municipalities with higher probability of demand for this fuel. To represent this criterion, we have utilized three sub-criteria:

   1.1. Number of vehicles registered in each municipality. The idea is that the higher the number of vehicles currently registered in the municipality, the greater the demand for FCV.

   1.2. Kilometers of national and regional roads. The idea is that the municipalities crossed by a greater number of kilometers of major roads are more likely to have a greater demand for hydrogen fueling stations. Thus, supply coverage for long distance travel is also considered.

   1.3. The income per capita declared in each municipality. Hydrogen vehicles will be more costly than traditional vehicles in the early stages. Therefore, it is more likely that demand for this new type of vehicle will come from municipalities with higher incomes.

2. Supply Criterion: renewable energies.

   Given the accessibility in Andalusia to renewable energies and in accordance with the criteria established in [I.4], in this chapter we take hydrogen from renewable sources into consideration. In order to minimize hydrogen transportation costs, in this chapter we welcome the existence of renewable energies (biomass, solar, wind and small-hydro) in the municipalities when locating the stations.

3. Environmental Criterion.

   In accordance with [I.4], we characterize each municipality by its pollution level and take this factor into account during the planning process. Municipalities with high pollution levels, or which have to be kept pollution-free, could become users of hydrogen fueling stations ahead of others.

It is worth mentioning why some criteria that were taken into consideration by other authors when tackling this problem have not been considered in this analysis. The case of Spain and Andalusia is specific, and different to the US and other countries; for example, the number of hydrogen facilities or fueling stations for this gas, or for natural gas, is almost nonexistent and does not merit consideration; average travel distances and road traffic density are different; and, finally, the hydrogen strategy in Spain and Andalusia must focus expressly on renewable hydrogen [I.2, I.23, I.24].

We here-below explain how we have quantified each of the aforementioned criteria.

1.2.1. Number of vehicles registered in the municipality

For each municipality, we have recorded the total number of vehicles registered in a year, considering that a municipality with more registered vehicles should be given priority when locating the fueling stations.

We consider a vehicle to be any engine powered vehicle, except motorcycles and special vehicles that, in theory, circulate. This consideration includes: cars, motorbikes, trucks, vans, buses and coaches, industrial tractors and others.

The data on the number of vehicles is for the year 2008 and they are the most updated data published officially by the Instituto de Estadística y Cartografía de Andalucía [I.25] to date. This information is depicted in Figure 1.1.

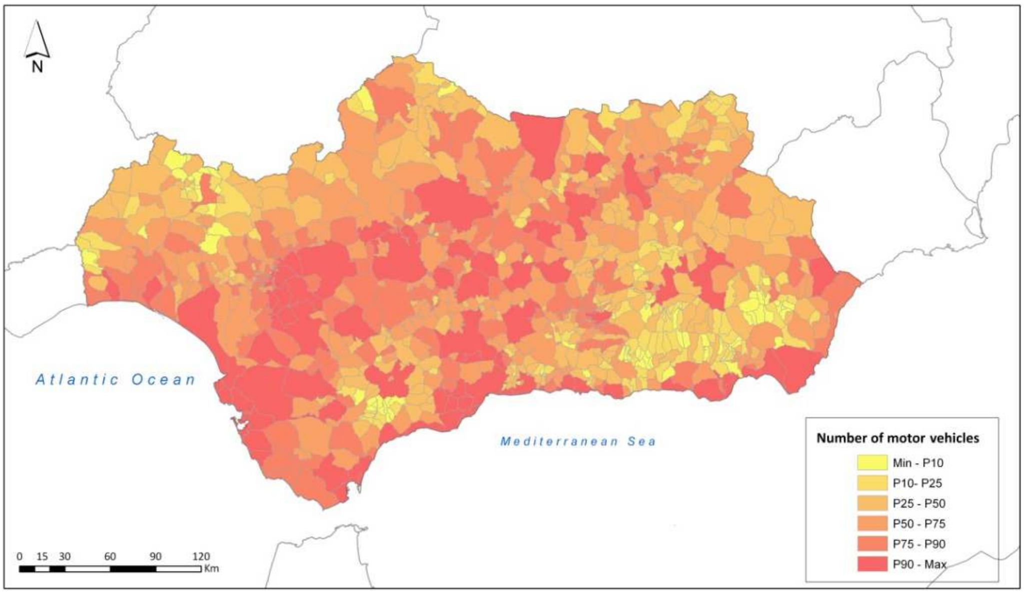

Figure 1.1.- Number of vehicles registered by municipality

1.2.2. Kilometers of road network in each municipality

As an indicator of traffic volume in a municipality we have used the number of kilometers of road network in each municipality. The idea is that the greater the traffic volume the greater the need for fueling. Of all the roads that exist in each municipality we have considered those that are owned by the State (Spain) and the regional government (in this case, Andalusia), given that they are the most important roads.

The information on national and regional roads was provided by the Ministerio de Fomento of Spain and the Consejería de Obras Públicas y Vivienda de la Junta de Andalucía, respectively, upon request by the author. In both cases, the data are for the year 2011 and are measured in kilometers of road network. The information obtained is shown in Figure 1.2.

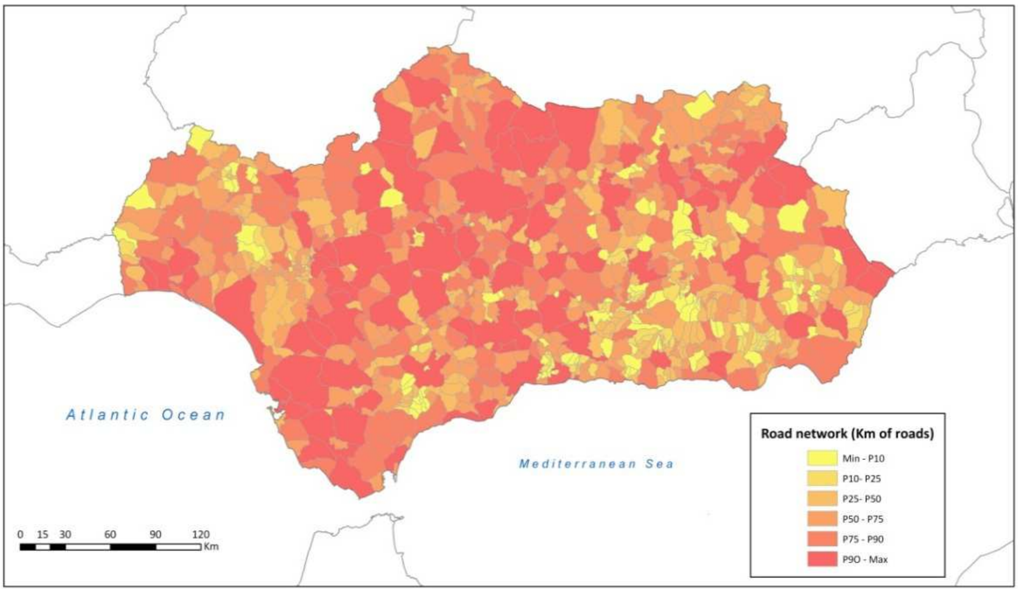

Figure 1.2.- Kilometers of road network in each municipality

1.2.3. Average income declared in each municipality

This criterion provides information on the average income in a municipality (see Figure 1.3). The higher the average income declared in a municipality, the greater the likelihood of it being able to migrate towards other more costly technologies.

To calculate this criterion we have divided, for each municipality, the aggregate PAYE (Pay as you Earn) by the number of PAYE income tax returns filed, where:

- PAYE – aggregate:

The aggregate information on the income tax paid by individuals (PAYE) has been obtained using the net incomes declared, which are obtained as a sum of the net revenues reported by type of activity, where these are: net income from work, net business income, net income from professional activities and other types of net income. This information comes from [I.25] (for 2008).

- PAYE – number of tax returns filed:

This shows the number of PAYE income tax returns filed in the corresponding year (2008 in this case). We must bear in mind that, in Spain, there is a minimum income threshold below which it is not compulsory to file a PAYE tax return. Once again, the data come from [I.25].

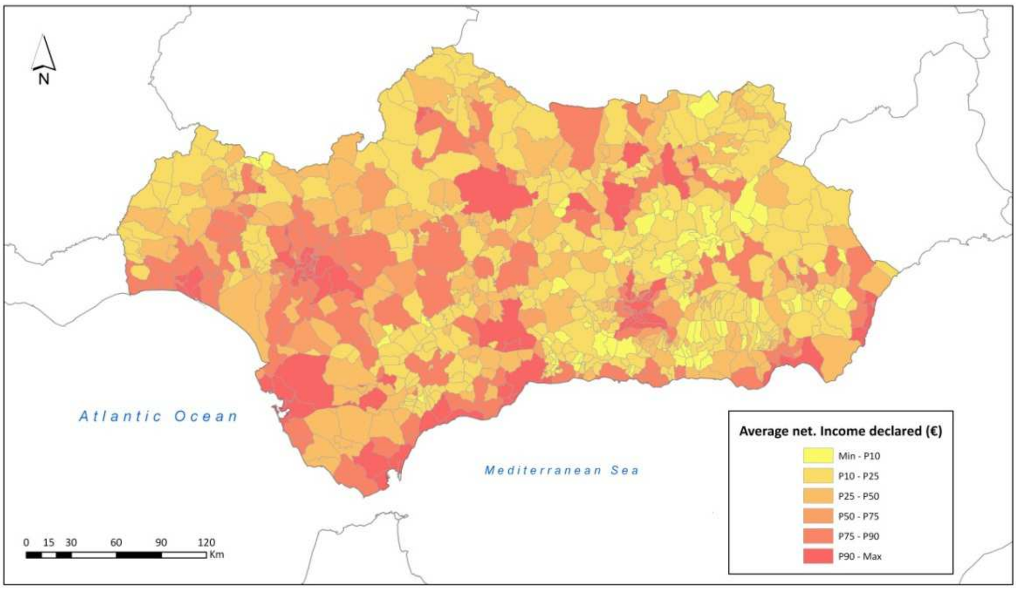

Figure 1.3.- Average income declared (€) in each municipality

1.2.4. Supply of renewable energies in the municipality

This criterion is the only one taken into account that is considered to be equivalent to the potential supply of hydrogen, and not to the foreseeable demand. We believe that, in an scenario that pursues a sustainable system based on renewable hydrogen, a municipality with greater availability of renewable sources will be more suitable than another with lower availability, when locating a hydrogen fueling station.

There could be two sides to this approach:

- It could be said that hydrogen can be transported from one municipality to another and, therefore, produced in a place other than where it is dispensed; nonetheless, local production lowers costs, minimizes risks, reduces the infrastructure required and meets regional energy policies; therefore, municipalities with the highest renewable potential will be given priority.
- It could be said that, in a transition stage, hydrogen generated from other sources different from renewable should be considered, such as, for example, that produced by natural gas reforming; however, once again, energy independence, security of supply, and compliance with environmental commitments, leads to a more positive value being put on greater presence of renewable energy sources in the municipality.

As potential renewable sources, we have considered solar energy, small hydro, wind and biomass. Figure 1.4 summarizes the information contained in this criterion. We here-below analyze each of these renewable sources and explain the steps taken to quantify them in each municipality.

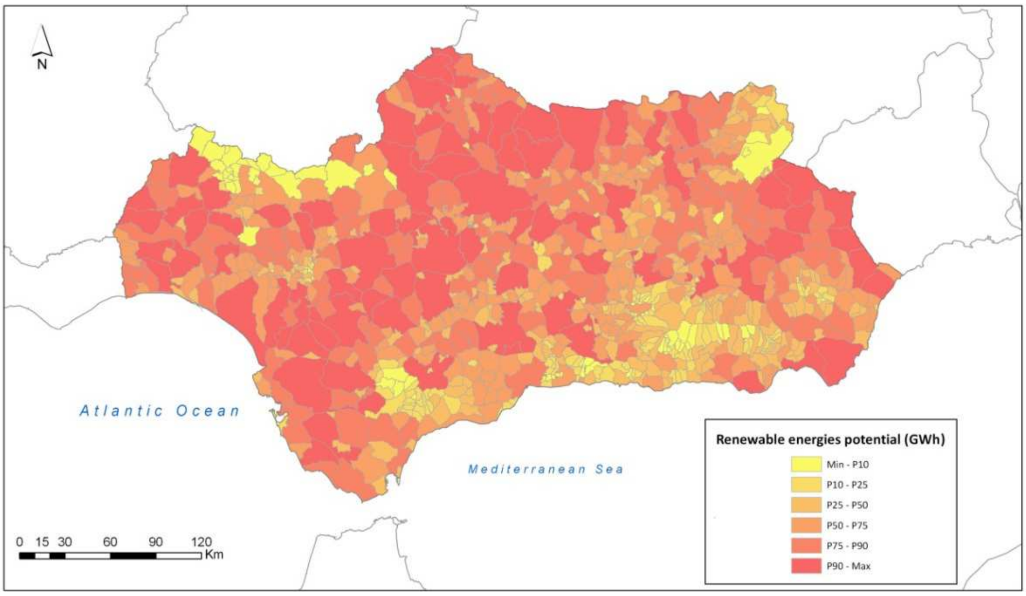

Figure 1.4.- Renewable energy potential (GWh) in each municipality

Solar energy

The calculation of Andalusia's solar potential has been one of the most complex; we must emphasize that we sought to discover the maximum solar energy possible that, from a theoretical but at the same time founded standpoint, could be converted into hydrogen annually.

To this end, we considered two processes for converting solar energy into electricity: solar thermal power plants and photovoltaic panels; we then analyzed the conversion of said electricity into hydrogen, utilizing electrolyzers.

To obtain the solar radiation received annually, both direct and diffuse, in each municipality, we used data from the Agencia Andaluza de la Energía [I.26]. Next, we multiplied the radiation, expressed in units of energy per square meter, by the useful surface area of each of the municipalities. We define the concept of "useful surface area" as "areas whose slope is <30%, at a distance of more than 100 meters from water channels, in areas not flooded by water surfaces, outside protected areas and removing urban areas and infrastructure". To gather this information, we utilized GIS tools.

We thus obtained the solar radiation data, in units of energy, annual aggregate, for each municipality, and separated it into its direct and diffuse radiation components, ready to be converted into electrical energy values.

In the case of solar thermal energy, we have considered the annual direct solar radiation in each municipality, and have applied a 16% factor of conversion into electricity [I.27]. In the case of photovoltaics, we have considered the annual total radiation (direct plus diffuse), and have applied a 10% conversion factor [I.28].

With these calculations, we have found that the potentially producible solar thermal electrical energy for all the municipalities of Andalusia is greater than the potentially producible photovoltaic electrical energy. Therefore, we have opted for thermal energy whenever possible, that is to say, whenever the "useful surface area" of the municipality is larger than 100 hectares, the minimum area required to install a plant of this type.

Finally, using the calculated value of maximum electrical energy to be generated annually in each municipality, from solar energy, we have moved into hydrogen, considering 67% efficiency when converting the electrical energy into the hydrogen's chemical energy using electrolyzers [I.29].

Wind power

In the case of wind power, our starting point was the number of "equivalent wind hours" for each municipality. This figure, provided by the Agencia Andaluza de la Energía shows, for each municipality, the "equivalent" hours of wind there would be for a specific wind turbine. Consequently, annual potentially producible energy is obtained by simply multiplying the output capacity of the wind turbine by the number of hours.

For each municipality, we have calculated the average “equivalent hours” for an 80 meters high, 2 GW wind turbine.

We then applied the same criterion of “useful surface area” in each of the municipalities: “areas whose slope is <30%, at a distance of more than 100 meters from water channels, in areas not flooded by water surfaces, outside protected areas and eliminating urban areas and infrastructure”. This “useful surface area” has been segmented into rectangles of 5 by 7 times the size of a standard wind turbine (2 GW), to obtain the maximum number of turbines that can be installed in each municipality.

Finally, we multiplied the number of wind turbines by their output (2 GW) and the “equivalent hours” for this type of wind turbine, obtaining the maximum electrical energy that can be generated annually by wind power in each municipality. We converted this quantity into hydrogen, as in the case of solar energy, considering 67% efficiency when converting the electrical energy into the hydrogen’s chemical energy using electrolyzers.

Small Hydro Power

To calculate the potential of this type of energy in each municipality, we have considered the existing facilities not exceeding 10 MW and, secondly, the sites that, though currently without a facility in operation, but having been used in the past, could be brought into production below that output [I.30].

Hence, we obtained the installed or installable outputs, and converted them into annual electrical energy by multiplying by the corresponding hours (1,500 hours/year flowing water facilities, and 2,100 hours/year dam toe facilities). Finally, we converted the electrical energy into hydrogen considering, once again, electrolyzers with a 67% conversion factor.

Biomass

The biomass potential of each municipality refers to the possibility of producing electricity, in each of them, from different wastes (not necessarily in the strict sense of “forest biomass”) and then converting it into hydrogen, using electrolyzers once again.

To this end, we started with the data provided by the Agencia Andaluza de la Energía on annual therms equivalent per municipality, considering agricultural waste (citric, olive, grape, tomato, cotton, rice, etc.), forest waste, livestock waste (pig slurry, cow manure, poultry manure, etc.), industrial waste (abattoirs, meat, glycerin, olive pits, mill residues, rice husk, wood, cork, nuts, beer, cotton, fisheries, etc.), energy crops and urban solid waste (used oil, wastewater, light sludge, parks and gardens, etc.).

In each case, we converted the total annual therms in each municipality into maximum annual electrical energy utilizing a 33% conversion factor, and that into hydrogen, once again with a 67% factor, considering the use of electrolyzers.

It is worth mentioning that there would be other ways, even more efficient, to convert biomass into hydrogen, by using, for example, gasification or reforming. However, for simplicity reasons, we have opted for the more conventional approach, considering that we are always comparing potentials and that a municipality with higher renewable potential than another will always be selected first if we ignore the other criteria.

1.2.5. Environmental pollution

In line with the PASENER [I.4], this criterion incorporates environmental pollution as one of the factors to be taken into account for optimal planning of hydrogen fueling stations. This approach considers that municipalities with high pollution levels will be more willing to embrace a less contaminating energy model.

The data on pollution levels in each municipality are for 2006 [I.31].

[I.31] analyzes the annual emissions of greenhouse gases by different activity sectors, considering acidifiers, ozone precursors and greenhouse gases, heavy metals and particles, organichlorine substances, and other organic and inorganic compounds. In this respect, for this study, the only gases taken into account are those deemed to be “greenhouse effect gases” in Decision 2002/358/EC of the European Council [I.32]: CH_4, CO_2, HFC, N_2O, PFC and SF_6.

From this inventory, and for each municipality, the quantity of each one of these gases has been converted into “tons of CO_2 equivalent” by using the GWP (Global Warming Potential) index (see Figure 1.5). This index provides a measure of a substance’s capacity to contribute to global warming via the greenhouse effect. The index is calculated over a one hundred year period, taking the carbon dioxide capacity as a reference, which is assigned, by convention, a GWP value of 1 [I.33] (See Table 1.1).

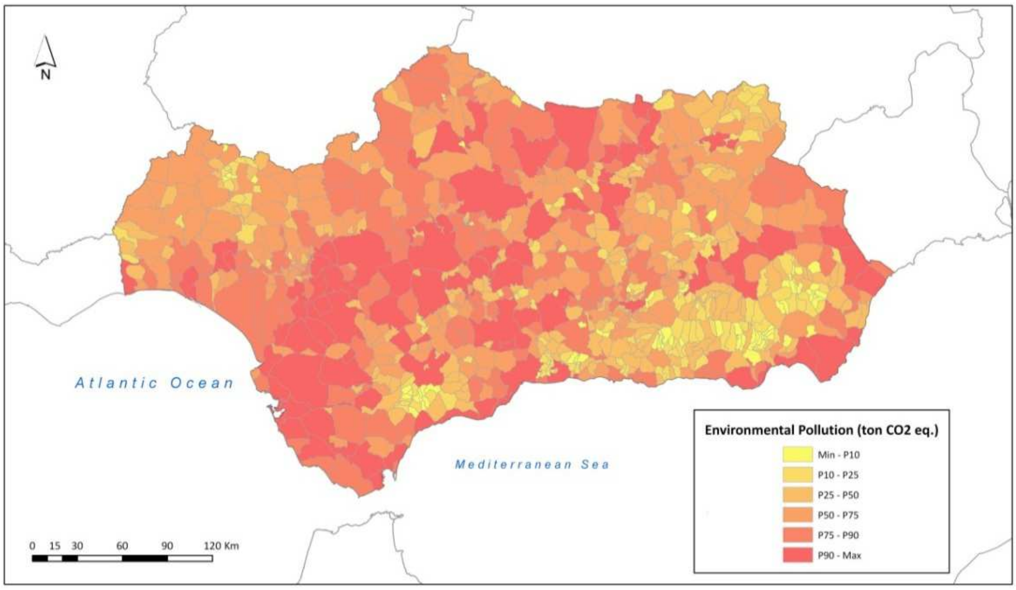

Figure 1.5. Environmental pollution in each municipality (tons of CO_2 equivalent)

Gas		Lifetime (years)	GWP Time Horizon		
			20 years	100 years	500 years
CH_4	Methane	12	62	23	7
N_2O	Nitrous oxide	114	275	296	156
PFCs	Perfluorocarbons	>2,500	8,000	>5,500	18,000
HFCs	Hydrofluorocarbons	1-250	9,400	10-12,000	10,000
SF_6	Sulfur Hexafluoride	3,200	15,100	22,200	32,400

Table 1.1.- GWP Index

1.2.6. Seven-figure summary

Table 1.2 lists the minimum and maximum values and the 10th, 25th, 50th, 75th and 90th percentiles for the values obtained for each of the criteria in the municipalities.

	Average net income declared (€)	*Road network: km of roads (km)*	*No. of motor vehicles (units)*	*Environmental Pollution (tons CO_2 equivalent)*	*Renewable energies potential (GWh)*
Minimum value	5,365.31	0.00	26.00	470.95	0.06
P10	9,597.33	0.00	336.40	2,643.07	932.21
P25	10,885.72	4.01	762.75	5,129.74	3,043.37
P50	12,488.08	11.07	2,103.00	13,966.89	10,597.20
P75	14,780.96	22.46	5,425.50	36,028.62	26,834.69
P90	17,850.43	41.65	14,133.00	92,507.75	54,854.64
Maximum value	29,517.67	230.72	489,643.00	6,602,738.49	304,587.18

Table 1.2.- Maximum and minimum values and 10^{th}, 25^{th}, 50^{th}, 75^{th} and 90^{th} percentiles for the values of the criteria in the municipalities

1.3. Ranking of municipalities

1.3.1. Methodology used to obtain the scores of each municipality

The score for each municipality was determined by personal interviews with three experts (*j*=1, 2, 3) on hydrogen and fuel cell technologies and on the Andalusian energy sector. These experts cover the different perspectives involved in the problem at hand as they belong respectively to:

- Abengoa (one of the most important private Andalusian company working in the field of renewable energy, including hydrogen as an energy vector),
- the University of Seville (an Andalusian University), and
- the Spanish Hydrogen and Fuel Cell Technology Platform.

We would mention that the opinions given by these experts reflect their own views and not necessarily those of their institutions.

The problem was structured in a hierarchy to facilitate the appraisal task for the experts (see Figure 1.6). The top of the hierarchy represents the goal, that is, to determine the best municipalities of Andalusia in order to establish a hydrogen fueling station. Underneath are the experts (E1, E2 and E3) who are going to make the judgments and appraisals. The next two levels are those of the different criteria and sub-criteria to be used in assessing the municipalities. As mentioned previously herein, we consider 3 criteria: Demand, Supply and Pollution. The Demand criterion is subdivided into three sub-criteria: number of registered vehicles, kilometers of roads, and official income per capita. Then, at the bottom level, we have the alternatives (municipalities). This way the decision problem is decomposed into separate parts.

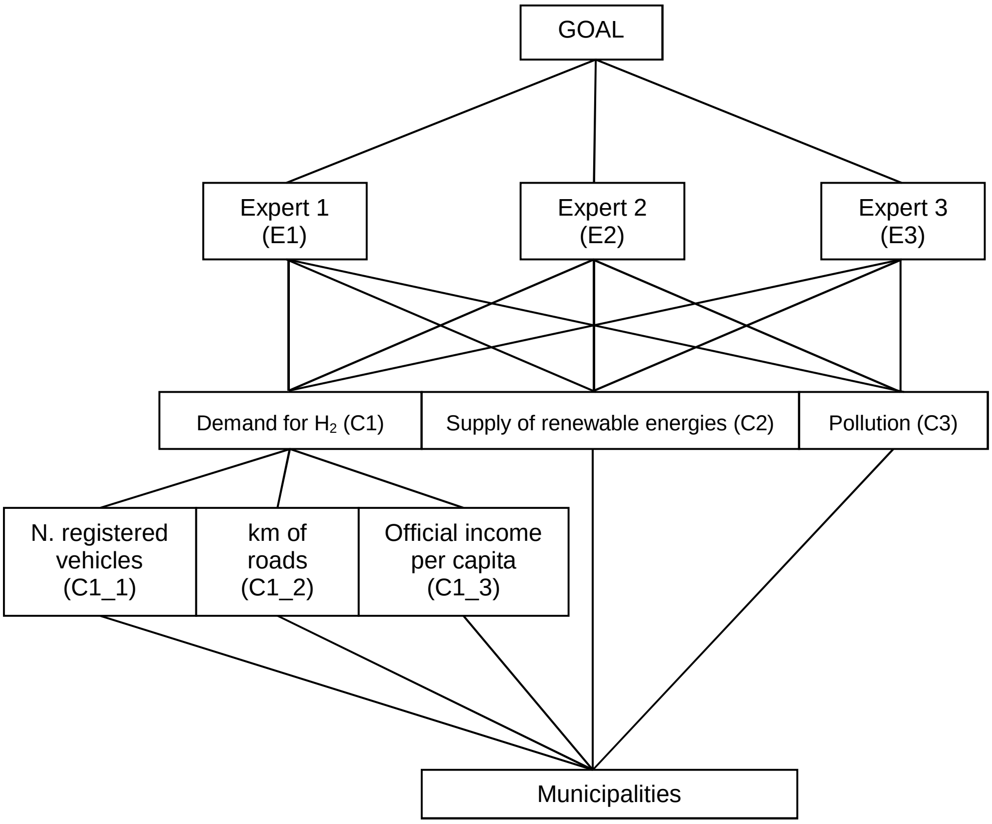

Figure 1.6.- Hierarchy structure

By using the Expert Choice software, the experts were required to make pair-wise comparisons between the different criteria (against the goal) and, lastly, between sub-criteria (against the “Demand” criterion) following the Analytical Hierarchical Process (AHP) methodology [I.34-I.36]. The pair-wise comparisons show in a 1 to 9 scale the relative importance of each criterion and sub-criterion with respect to the upper level in the hierarchy. These comparisons are represented in the comparison matrices. Tables 1.3 and 1.4 show the comparison matrices for one expert.

	Demand	Supply	Pollution
Demand	1	1	2
Supply	1	1	2
Pollution	½	½	1

Table 1.3. Pair-wise comparison matrix for the criteria level

	No. vehicles	km of roads	Income per capita
No. vehicles	1	¼	½
km of road network	4	1	2
Income per capita	2	½	1

Table 1.4. Pair-wise comparison matrix for the sub-criteria level

If the comparison matrices are consistent enough to provide reliable criteria and sub-criteria weights, the weights for each level can be calculated using the formula [I.35]:

$$Aw=\lambda_{\mathrm{Max}}w, \qquad \text{Eq. [1.1]}$$

where A denotes the comparison matrices, λ_{Max} the largest eigenvalue of A, and w is the corresponding eigenvector. The weight vector is obtained by dividing the elements of w by their sum. The consistency of the comparison matrices was checked using the Consistence Ratio (CR) proposed by [I.35, I.37]. As recommended [I.35, I.38], the value of CR for all the comparison matrices was less than 10%.

The weight of each sub-criterion is multiplied by the weight of the Demand criterion to obtain a global weight for each sub-criterion. The global weights are weights expressed in terms of the whole hierarchy. Therefore, for each expert j, we have a final global weight vector w^* composed of 5 elements (w_{ij}^*, i=1,…,5): the global weights of the Supply and Pollution criteria, and of the three sub-criteria.

Next, the experts were also required to evaluate the performance of the municipalities under the 5 criteria and sub-criteria. Due to the large number of municipalities (s=1,…,770) and the quantitative character of the data, the experts had to provide functions ($V_{ij}(x)$) to convert the values of each criterion (or sub-criterion) in each municipality s to a common 0-1 ratio scale. This scale determines how well each municipality accomplishes each criterion, with 1 being the value assigned to the top performers. Figure 1.7 shows the function provided by one expert to the km of roads sub-criterion.

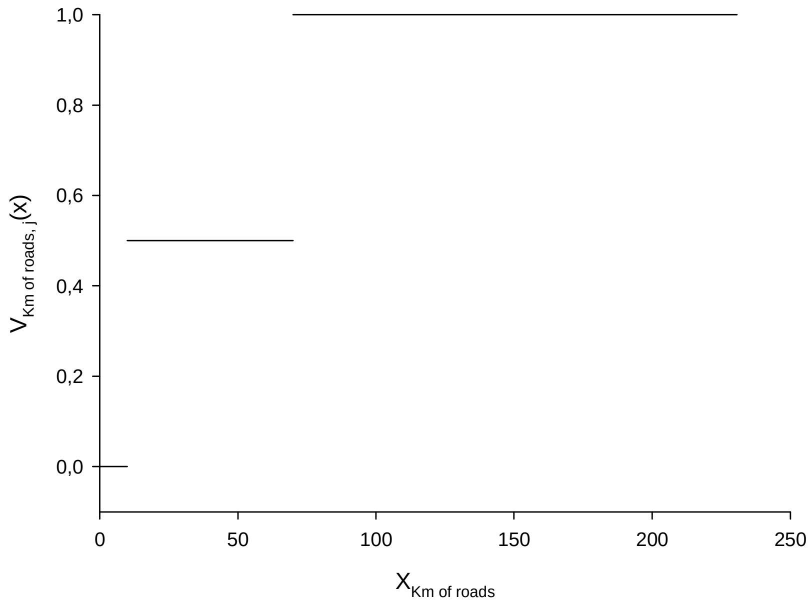

Figure 1.7.- Step function provided by one expert for the km of roads sub-criterion

For each expert, the values of the performance of each municipality under each criterion $V_{ij}(x_{is})$ are multiplied by the respective global weight of each criterion (or sub-criterion) w_{ij}* and additively aggregated, resulting in a positive ratio-scale score for each municipality, as shown in Eq. [1.2]:

$$p_{js} = \sum_{i=1}^{5} w_{ij} * V_{ij}(x_{is}). \qquad \text{Eq. [1.2]}$$

The score for each municipality is determined independently from the other municipalities, and range from 0 to 1, where a score of 1 means that the municipality is a top performer with respect to the other municipalities. As a consequence, removal of municipalities by the decision-maker due to external factors will not affect the outcome. These scores are ratio-scale and can be used as objective function coefficients in an integer optimization problem [I.39].

A final score p_s for each municipality is obtained following the weighted arithmetic mean method (WAMM) [I.40]. This approach was chosen as it was not possible to achieve a consensus among the experts regarding the scaling functions $V_{ij}(x)$ (mainly because they were geographically distant persons) [I.41]. Giving the same importance to each expert, final score p_s for each municipality is calculated averaging the scores p_{js} among the experts.

1.3.2. Ranking of municipalities

The scores obtained in the previous Section allow us to rank the 770 municipalities according to their suitability for hydrogen fueling station implementation in terms of the supply, demand and environmental criteria. The ranking obtained does not necessarily mean the decision-maker will go through the ranking employing a strict top-down approach. There could be external factors that lead the decision-maker to select, for example, the tenth placed municipality ahead of the third placed municipality. However, it clearly informs the decision-maker that it would be preferable to invest in a municipality located in the top decile rather than in a municipality located in the bottom decile.

The results obtained are summarized in Figure 1.8. This figure groups the municipalities in 6 equal groups according to their scores. The ranking shows that highest scores are achieved by municipalities in western Andalusia. Of the top 20 municipalities, only 5 are in eastern Andalusia. Therefore, western Andalusia could be taken as a promising starting out point to establish hydrogen fueling stations in Andalusia in a first phase.

The advantage of this approach compared with the exclusive use of GIS is that it allows ranking of the different areas according to their suitability in terms of a number of criteria, and not only the identification of areas that meet some criteria.

Finally, we would emphasize that this ranking is the result of a multi-criteria approach and, therefore, we have not only considered demand criteria, but supply and environmental criteria too. Moreover, the renewable hydrogen approach adopted has resulted in the interviewed experts tending to give importance to this criterion when evaluating the municipalities. This fact explains, for example, that there does not necessarily have to be a correlation between the number of existing gas stations in the municipalities and the score obtained. Nonetheless, 36.7% of existing gas stations in Andalusia in 2011 are in the top 50 municipalities of the ranking (6.5% of the municipalities).

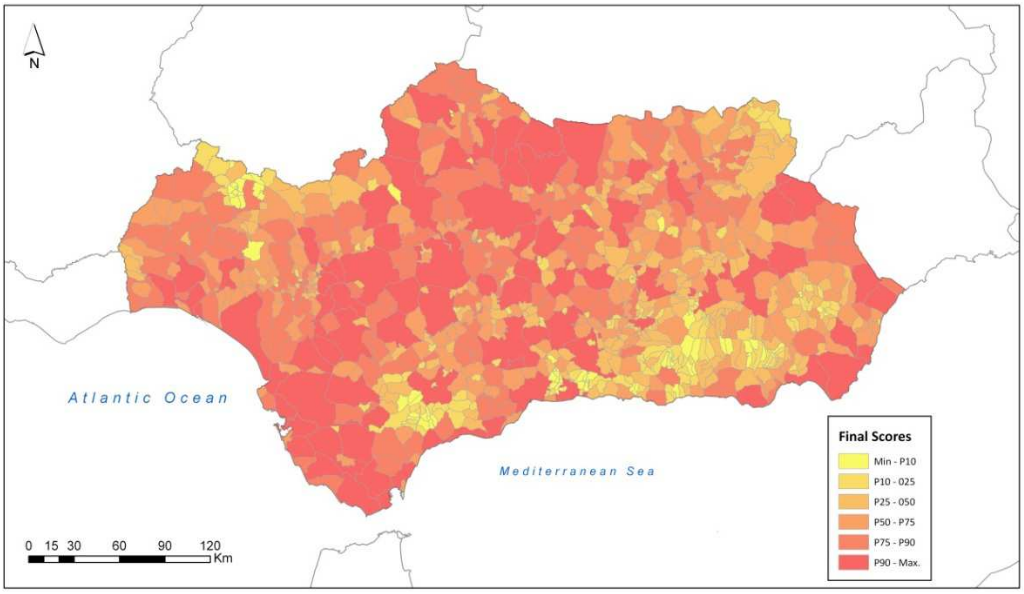

Figure 1.8.- Ranking of municipalities according to their score

1.4. Optimal planning of a network of hydrogen fueling stations in Andalusia

1.4.1. Model

The purpose of this section is:

- to establish a minimum number of hydrogen fueling stations in Andalusia that routs the chicken and egg paradox, and
- to geographically position, throughout Andalusia, said fueling stations optimally.

This planning would correspond to a more advanced stage of the hydrogen vehicle introduction process in Andalusia.

To carry out this planning, we use the scores obtained in the above section to define the objective function of an optimization problem. The use of these types of scores in the objective function of an optimization problem is a standard approach in literature [I.42 – I.44]. Our aim is to select the municipalities with the highest score, but avoiding the selection of two very neighboring municipalities. The idea is to design a network consisting of as few stations as possible (minimum cost), but of sufficient number to solve the chicken and egg problem (supply Andalusia).

Our optimization problem can be formulated as:

$$Max \sum_{s=1}^{770} p_s Z_s - \gamma \sum_{s=1}^{770} \sum_{n=1}^{770} Y_{sn} Z_s Z_n \qquad \text{Eq. [1.3]}$$

where Z_s and Z_n are binary decision variables taking a value of 1 if the municipality s is chosen to establish the hydrogen station and 0 otherwise, Y_{sn} are binary variables taking a value of 1 when two municipalities s and n are too close (in relation with a given figure) and 0 otherwise, and γ is a penalty coefficient that prevents the selection of two very neighboring municipalities. We set $\gamma = 500$. The choice of too neighboring municipalities is penalized because we aim to design a network of hydrogen fueling stations in Andalusia at the lowest cost. Hydrogen fueling stations must be close enough to one another to make fueling easy anywhere in Andalusia, but far enough apart to avoid unnecessary extra-costs in this implementation stage. The distances between municipalities are calculated using a single origin-destination point for each municipality.

The outstanding feature of this model is that it not only helps to determine the better candidate municipalities but also the minimum number of hydrogen fueling stations to be established in Andalusia to supply the entire region. However, this feature introduces more complexity when it comes to resolving the optimization problem.

1.4.2. Results of the optimization problem

To optimize Eq. [1.3] we consider that two municipalities are too close when less than 25 kilometers apart. Therefore Y_{sn}=1 for distances of less than 25 km.

The optimization problem was solved by simulated annealing [I.45]. Simulated annealing is a local-search, meta-heuristic method used especially to deal with optimization problems characterized by a discrete but very large configuration space, where the global optima is hidden among many local optima. The key feature of simulated annealing is that it allows to escape from the local optima by taking downhill steps (that is to say, steps that worsen the objective function value) [I.46]. In each iteration, two types of configurations are generated: improving solutions that lead to a larger value of the objective function, and non-improving configurations that have a lower value of it. Improving configurations are always accepted, but also some of the non-improving ones. Therefore, it is possible to escape from a local optima with the hope of finding the global one. The probability of accepting non-improving configurations depends on a temperature parameter, which is typically nonincreasing with each iteration of the algorithm. The lower the temperature, the less frequent down-hill steps are accepted.

Using this meta-heuristic, we performed several simulations which started from different seeds and temperatures. Figure 1.9 shows the 101 municipalities selected in the solution with the highest objective function value.

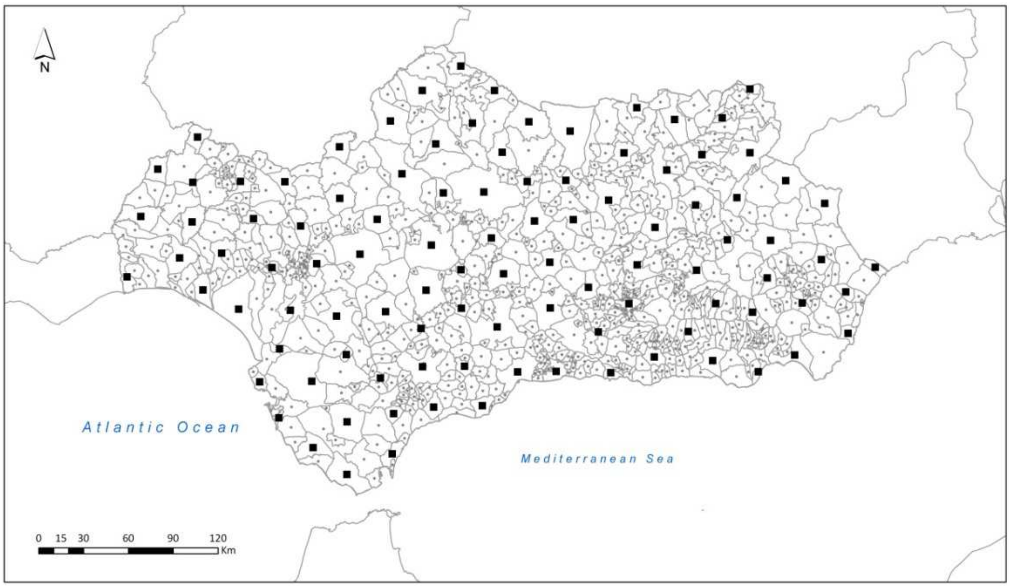

Figure 1.9.- Municipalities selected for hydrogen fueling stations to provide coverage for all Andalusia. The black squares are the centroids of the chosen municipalities. For reference, also the non-chosen ones are indicated (small circles)

Modeling of the problem guarantees that the distance from any “not-selected” municipality (or, to be more precise, its centroid) to one of the 101 selected municipalities (to their centroids) is always less than 25 km: to be precise, the maximum distance that appears is 24.24 km.

If we analyze the minimum distances obtained between the centroids of selected municipalities, we find that the minimum distance (between selected “neighboring” municipalities) is 25.02 km (as was to be expected, it is greater than 25, or both would not have been selected) and the maximum is 37.42 km. The latter is less than 50, but this did not necessarily have to be so; what would be normal is that if the distance between two municipalities were greater than 50 km, a fueling station would be installed at the halfway point but, logically, this only occurs if that municipality exits. Two large municipalities with neighboring surface areas would have resulted in both being selected (distance between centroids greater than 25 km), but both fueling stations would have been very far apart.

The aforementioned maximum distance of 37.42 km is assimilable to the “Don’t worry distance” (the distance between hydrogen stations that drivers consider sufficient), concept utilized by [I.7]. Therefore, we implicitly assume in the model that early-adopters would be willing to travel, as a maximum, 37.42 km to refuel. This distance would be equal to about 8% of the autonomy of the 2009 Honda FCX Clarity (460 km).

1.5. Conclusions

The use of vehicles powered by hydrogen from renewable sources can be a viable alternative for Andalusia, given its accessibility to renewable energies and the problems of energy dependence and pollution resulting from the current energy model. However, the introduction of this type of technology requires an initial infrastructure that solves the classical chicken and egg problem, minimizing the cost of the initial deployment of the new technology.

With this chapter we aim to contribute to the optimal planning of this transition process in this region. To this end, we have utilized AHP to rank the 770 municipalities of Andalusia attending to their suitability for a hydrogen fueling station. This suitability is defined by multiple criteria (number of vehicles, kilometers of roads, income per capita, potential of renewable energies, and environmental pollution, i.e. demand, supply and environmental criteria), following the guidelines suggested in the Andalusia Sustainable Energy Plan 2007-2013.

The results obtained from this ranking show that western Andalusia could be considered a promising starting point to establish hydrogen fueling stations in a first phase in Andalusia. The best areas could be considered as clusters, in which selected municipalities and corridors would be equipped with a number of fueling stations to supply early-adopters. Thus, AHP has proven to be a useful tool for planning the placement of the fueling stations when possible potential locations are characterized using more than one criterion.

We then designed a network of hydrogen fueling stations aimed at providing coverage for all Andalusia and solve the chicken and egg problem. To design this network, we avoid the choice of municipalities less than 25 kilometers apart. The results indicate the 101 hydrogen fueling stations would suffice to supply all Andalusia under these conditions and, furthermore, allow locating of these fueling stations. This network guarantees that the distance from any “not-selected” municipality to one of the 101 selected municipalities is always less than 25 km. These results could be taken as a starting out point when debating possible locations for hydrogen fueling stations in Andalusia.

For reference, let us indicate that there are 1,438 gasoline stations in Andalusia (January, 2011).

Obviously, the locations obtained are contingent upon, among other factors, the criteria considered to characterize the municipalities, the optimization criteria and the minimum distance used. Therefore, further research is needed to explore alternative approaches to perform the planning. Finally, in this study, we have not explored the possibility of installing more than one hydrogen fueling station in the municipalities that, given their special characteristics, could require more than one. This is because we have preferred to adopt a more qualitative approach, leaving estimation of infrastructure costs for research in the future.

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CHAPTER TWO

ANALYSIS OF A HYDROGEN STATION ROLL-OUT STRATEGY TO INTRODUCE HYDROGEN VEHICLES IN ANDALUSIA

Abstract

The issue of the distribution of a sufficient infrastructure of hydrogen fueling stations, to enable meeting of the initial demand and to satisfy the different roll-out scenarios, has been addressed by different authors, in different geographies, and with different methods and approaches. In this chapter, we use a spatial approach to study the prospect of a sequential roll-out strategy from the present time to 2030 for Andalusia, a region in southern Spain. In every stage, we identify main nodes and clusters by examining in which areas of this region the roll-out, of fueling stations should start. Finally, we estimate the number and size of fueling stations for every stage, as well as the investment required for this infrastructure roll-out based on the estimated costs for each type of hydrogen fueling station over the aforesaid time.

2.1. Introduction

Some of the world’s leading car manufacturers believe that by 2015 they will have “a quite significant number” of hydrogen vehicles on the road [II.1]. However, this means that a minimal infrastructure will have to be deployed, as efficiently as possible, in a short period of time. Roll-out of this network of hydrogen fueling stations would have to start before said year, and be reasonably developed 15 years later on, that is to say, by 2030, as proposed by the EU [II.2, II.3].

This issue of the distribution of a sufficient infrastructure of hydrogen fueling stations, to enable meeting of the initial demand and to satisfy the different roll-out scenarios, has been addressed by different authors, in different geographies, and with different methods.

From Kuby et al. [II.4] and Dagdougui et al. [II.5], we highlight two different approaches when dealing with locating fueling stations: optimization (operations research) methods and GIS based approach. The optimization approach makes use of optimization models to attain an efficient infrastructure design, according to some specific criterion or criteria. According to [II.6], these optimization-based approaches can be classified into two groups, depending on the geometric representation of demand: models for point-based demand [II.7-II.9] and flow-based demand [II.4, II.6].

The GIS based approach focuses on the spatial dimension to locate the fueling stations. Fueling station locations and networks are identified and/or evaluated using multiple spatial criteria [II.10-II.12]. The work presented in this chapter fits the latter approach. The aims of this chapter are to:

- design a roll-out strategy based on nodes and clusters for Andalusia in the coming years, by examining in which areas of this region the roll-out of fueling stations should start,
- and estimate the total investment required for this roll-out. In order to do so, we calculate the costs of different sizes and technologies for hydrogen fueling stations.

The structure of this chapter is as follows. Section 2.2 develops the procedure followed to design the roll-out strategy. This procedure is applied in Section 2.3 to the case of Andalusia. Section 2.4 estimates the figures and costs associated with the roll-out strategy in this region. Finally, Section 2.5 contains the main conclusions.

2.2. Procedure to design a roll-out strategy

Assume that the *n* subregions that compose a region are ranked according to their suitability to accommodate hydrogen fueling stations. This ranking may be obtained by many different procedures and combining different procedures or criteria [II.13-II.15]. From this ranking, we define a progressive roll-out strategy based on three main assumptions:

- Hydrogen users will not be distributed evenly throughout the region, and therefore, initially, the early adopters will be grouped in certain municipalities.
- These first areas selected will be, precisely, those that were deemed to be the “most suitable” in our ranking.
- With the passing of time, the number of municipalities that engage in the hydrogen economy will be increased in each stage by locating fueling stations in them.

This sequential roll-out strategy is defined through the concepts of main node, cluster and interconnection node. A main node is an area (subregion) selected to locate fueling stations due to its suitability. A cluster is a group of main nodes that are close enough together and overall represent at least a predefined percentage of population. An interconnection node is a subregion that is selected within a cluster to locate fueling stations when the main nodes are farther apart than a predefined distance. Its aim is to “connect” the main nodes within a cluster, reducing the distance a driver should have to travel to be able to fill his/her car, so improving the perceived fuel availability.

The stepwise procedure is as follows:

1. Select the *m* units first from the ranked list of *n* subregions, so that the previously defined total targeted population is supplied.
2. Select (following a top-down approach) the *r* ($r<m<n$) first municipalities (i.e., main nodes) in the ranking, that represent at least the targeted percentage of the total population for that stage, and are less than d_1 kilometers from some other selected node, considering main highways (i.e., close enough). These main nodes that are close enough and supply a certain level of population (i.e., critical mass) form a cluster.
3. If the main nodes that form the cluster obtained in step 2 are further than d_2 kilometers away, check the list of the *m* top ranked subregions to see if there is a possibility of selecting any subregion from the list, geographically located along the highways that link them, to be used as interconnection nodes within a single cluster (therefore, $d_2 < d_1$.).
4. Repeat steps 2 and 3, for each stage, until the total targeted population is supplied.

The number of fueling stations to be located in each node is calculated according to the following criteria:

- Each main node will have at least two fueling stations because, if they have only one, it would create great insecurity among users (if the only fueling station was not operational, for some reason or other, they would not be able to refuel) [II.16].

- The number of fueling stations in each main node will be calculated taking into account the total number of vehicles to be supplied, and the estimated capacity of the fueling stations (which will be increased progressively).
- The interconnection nodes have only one fueling station, since they only serve travelers, and not the local demand; however, note that an interconnection node may become a main node in a future stage.

2.3. Application. Roll-out strategy for the case of Andalusia

The starting point of this chapter is the result of previous research in which the authors characterized and assessed the 770 municipalities existing in Andalusia in 2009, according to their suitability to accommodate hydrogen fueling stations [II.17] (so, in our case, n=770). The average area of these municipalities is approximately 113.8 km^2.

In [II.17], the authors used different criteria to determine the most suitable areas. The 770 municipalities were characterized in terms of criteria of supply (availability of renewable energies) and of demand (kilometers of road network, number of registered vehicles, per capita income, and pollution). Finally, based on interviews with experts and the use of the Analytical Hierarchical Process[3], the authors obtained an assessment for each municipality reflecting its suitability for the establishment of hydrogen fueling stations. These assessments resulted in a ranking of the municipalities from the most favorable municipality to the least favorable.

Our aim in this chapter is to design a roll-out strategy to cover at least 30% of the total population of Andalusia by 2030. With this purpose, we set m=35 municipalities (subregions), since these municipalities contained more than 30% of the total population in 2011. The top 35 municipalities in the list were Córdoba, Jerez de la Frontera, Seville, Málaga, Jaén, Arcos de la Frontera, Écija, Antequera, Carmona, San Roque, Alcalá de Guadaira, Utrera, Huelva, Osuna, Úbeda, Ronda, Lucena, Baena, Medina-Sidonia, Morón de la

[3] The Analytical Hierarchical Process is a methodology that allows the relative weight of multiple criteria (in terms of their importance to achieve a goal) or multiple alternatives with respect to a criterion (in terms of performance of the alternatives on that criterion) to be assessed by pairwise comparisons (see [II.18, II.19]). Applying this methodology, the average weights of the criteria that resulted from the experts' pairwise comparisons in [II.17] were: availability of renewable energies (0.24), kilometers of road network (0.24), number of registered vehicles (0.16), per capita income (0.10), and pollution (0.26).

Frontera, Andújar, Loja, Hinojosa del Duque, Montoro, Huescar, Fuente Obejuna, Villanueva de Córdoba, Hornachuelos, Los Barrios, Marchena, Véjer de la Frontera, Marbella, Almería, Priego de Córdoba, and Espiel.

These top 35 municipalities are mainly grouped in the western region of Andalusia, constituting what could be a good starting point in the development of hydrogen infrastructure for the transportation sector.

From this ranking, we applied the stepwise procedure explained in Section 2.2, obtaining the following roll-out strategy for Andalusia in 2014, 2015, 2020, 2025 and 2030. In this roll-out strategy, we considered d_1=180 km and d_2= 90 km. These distances represent, respectively, one-third and one-sixth of the average driving range of the FCVs (around 540 km)[4].

First stage; year 2014, *r*=3

For 2014 we select *r*=3, in order to cover at least 8% of the population of Andalusia; we obtain:

Three main nodes: Cordoba (#1 in the list), Jerez de la Frontera (#2) and Seville (#3).

Two connection nodes: Carmona and Écija.

(See Figure 2.1, first map).

Second stage; year 2015, *r*=4

For this year, another main node is added: Malaga (#4).

Two more connection nodes added: Lucena and Antequera.

(See Figure 2.1, second map).

Third stage; year 2020, *r*=10

For 2020 we would have:

Three more main nodes added: Jaen (#5), Arcos de la Frontera (#6), and San Roque (#10).

Three connection nodes become, due to their importance, main nodes: Écija (#7), Antequera (#8) and Carmona (#9).

Three new connection nodes appear: Medina Sidonia, Andújar and Marbella.

(See Figure 2.1, third map).

Fourth stage; year 2025, *r*=14

[4] It is assumed this average driving range after considering the driving range from the models Toyota FCHV-adv, Honda FCX Clarity, and Hyundai ix35 FCEV.

For 2025, the distribution would be:

Four new main nodes: Alcala de Guadaira (#11), Utrera (#12), Huelva (#13) and Osuna (#14), and there would be no new connection nodes.

With this, the total count would be:

Main nodes in: Córdoba (#1), Jerez de la Frontera (#2), Seville (#3), Málaga (#4), Jaén (#5), Arcos de la Frontera (#6), Écija (#7), Antequera(#8), Carmona (#9), San Roque (#10), Alcalá de Guadaira (#11), Utrera (#12), Huelva (#13), Osuna (#14).

Connection nodes in: Lucena, Medina-Sidonia, Andújar and Marbella.

(See Figure 2.1, fourth map).

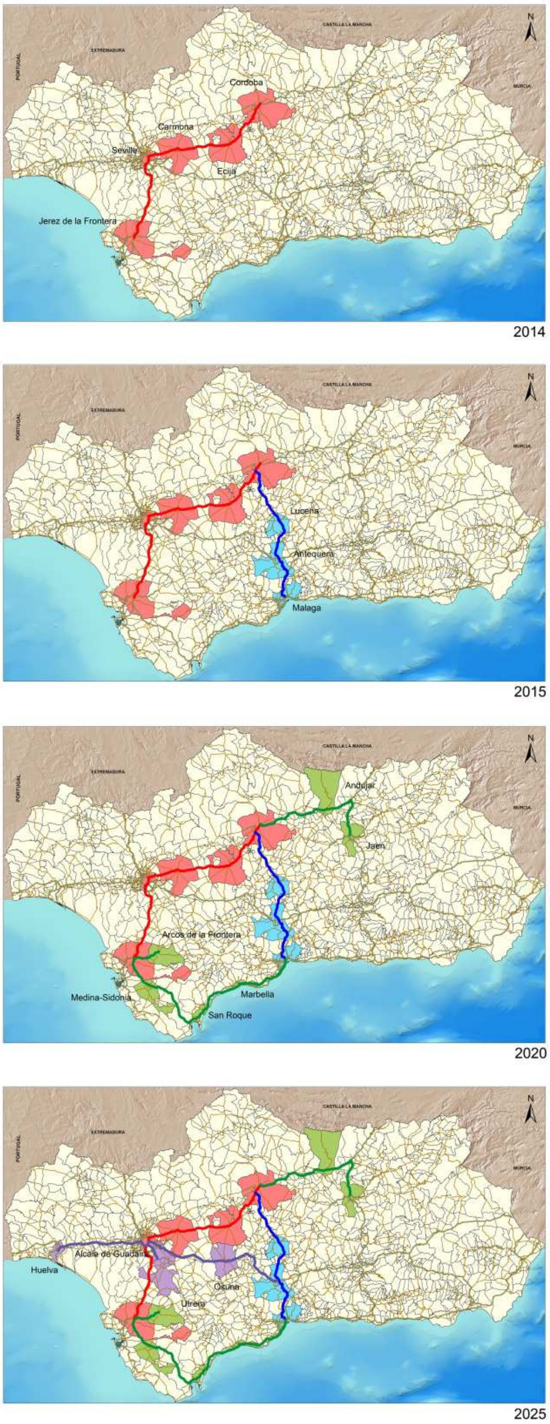

Figure 2.1.- Roll-out strategy 2014 – 2025

Fifth stage; year 2030, *r*=35

All the *m* municipalities are considered main nodes (see Figure 2.2).

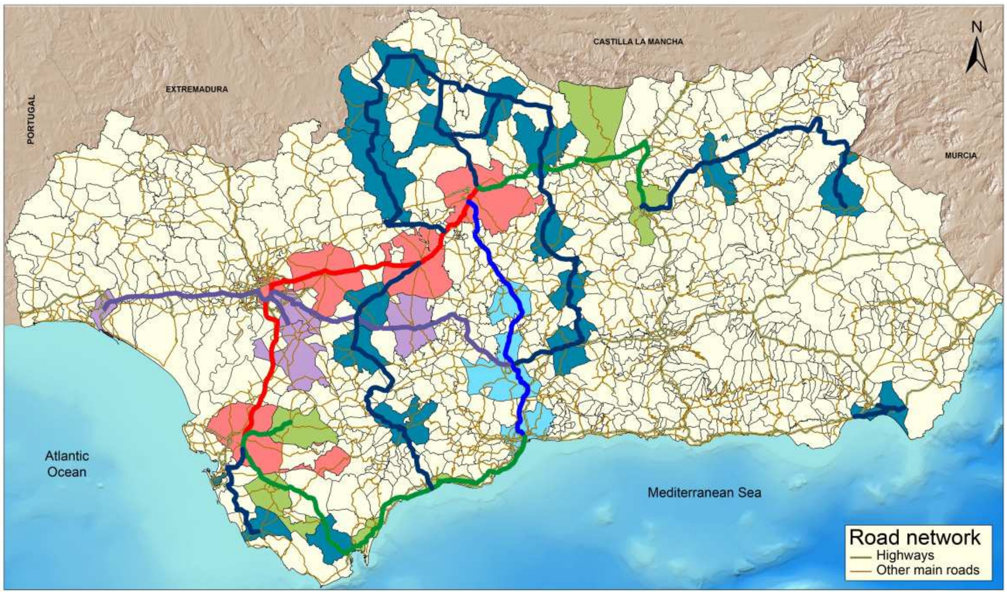

Figure 2.2.- Roll-out strategy 2025 - 2030

2.4. Estimation of the necessary investment in Andalusia

The estimation of the investment associated with this roll-out strategy requires planning of the number of hydrogen fueling stations to be implemented. This figure will be related in turn to the estimated number of hydrogen vehicles to be supplied. These figures are estimated in Sections 2.4.1 and 2.4.2. The unit costs of a fueling station for different sizes and technologies are estimated in Sections 2.4.3 (short term) and 2.4.4 (long term). The unit costs in the medium term (2016-2019) are extrapolated from the others. All these results are used as input to estimate the costs of the roll-out strategy (Section 2.4.5).

Due to the fact that the first fueling stations will supply fewer vehicles than those established in the period 2020-2030, it is assumed that the first stations will be smaller in capacity.

For this study we are going to consider that the average daily consumption of a hydrogen fuel cell vehicle is 0.6 kg as reported by [II.20-II.21]. Thus, a fueling station with the capacity to supply 100 kg/day of hydrogen will be able to cover the needs of a fleet of 166 hydrogen vehicles.

2.4.1. Penetration of hydrogen vehicles in Andalusia

One of the most comprehensive studies to date on possible scenarios of hydrogen economy penetration in Europe through the transportation sector is HyWays [II.22]. In its conclusions, this project establishes three penetration scenarios for hydrogen vehicles: high penetration, medium penetration and low penetration, based mainly on two criteria: policy support and learning.

If we take the middle scenario (medium penetration), the percentages for the penetration of hydrogen vehicles compared to the total vehicle fleet over the years is as shown in Table 2.1.

In the case of Andalusia, we can estimate the number of vehicles based on the current figure (5,365,010 vehicles registered in 2011 [II.23]), and considering a constant AAGR (Annual Average Growth Rate) up to 2030. We estimate this AAGR based on growth in the period 2005-2010 (AAGR = 2.74% [II.24]). Thus, and applying the percentages from HyWays, we estimate the expected number of hydrogen vehicles in 2014, 2015, 2020, 2025 and 2030 for Andalusia (see Table 2.1).

Year	*2014*	*2015*	*2020*	*2025*	*2030*
Expected total fleet of vehicles	5,818,208	5,977,627	6,842.686	7,832,933	8,966,485
Percentage of hydrogen vehicles	0.01	0.02	1.20	5.10	11.90
Hydrogen vehicles	582	1,196	82,112	399,480	1,067,012

Table 2.1.- Hydrogen vehicles penetration according to HyWays

2.4.2. Estimation of the number of hydrogen fueling stations

As mentioned earlier, the number of hydrogen fueling stations is assumed to grow annually to allow the emergence of the estimated demand by hydrogen vehicles (see Table 2.1).

Therefore, and considering the number of vehicles estimated above, a possible roll-out for Andalusia could be that shown in Table 2.2. The explanation is given in 2.4.2.1 to 2.4.2.3.

Year	2014	2015	2020	2025	2030
Vehicles	582	1,196	82,112	399,480	1,067,012
Main nodes	3	4	10	14	35
H_2 FS in main nodes	6	12	70	210	525
Connection nodes	2	4	4	4	0
H_2 FS in connection nodes	2	4	4	4	0
Total nodes	5	8	14	18	35
Total H_2 FS	8	16	74	214	525
Vehicles / FS (approx)	70	80	1,100	2,000	2,000

Table 2.2.- Nodes and fueling stations (FS)

2.4.2.1. The period 2014-2020

In this period, the number of motor vehicles using hydrogen, for passenger transportation, has risen from almost zero to more than 80,000 by 2020.

As stated in section 2.3, roll-out would start with three nodes, and gradually increase to 10 by 2020, with demand covered by a total of 70 fueling stations in these nodes. The roll-out of nodes will take place from the present time (zero nodes); the initial approach is that the fueling stations will supply mostly non-renewable hydrogen, so as to facilitate roll-out of this technology.

2.4.2.2. The period 2020-2025

For 2025, we propose a mix of hydrogen fueling stations to ensure that at least 30% of the gas comes from renewable sources.

The main figures for this period are: increase in the number of vehicles from more than 80,000 to close to 400,000, of main nodes from 10 to 14, and of fueling stations within these nodes to 210.

2.4.2.3. The period 2025-2030

By 2030, 75% hydrogen from renewable sources is assumed[5]; the m = 35 municipalities on the list are considered main nodes, for all of Andalusia. This approach guarantees that the "most suitable municipalities" are used to accommodate hydrogen vehicles, applying a cluster strategy (see Figure 2.2).

[5] The Spanish partners of HyWays established that most of the hydrogen will be produced from renewable sources in the future in Spain. The main reason is that there's no coal, petrol or natural gas in this country, and Spain is in a moratorium on nuclear energy [2.25].

An average of 15 stations per main node is considered, representing a total of 525 fueling stations, and an average of 2,000 vehicles served per fueling station.

2.4.3. Cost of hydrogen fueling stations in the first two years (2014-2015)

Several authors have worked on the calculation of the cost of implementing hydrogen fueling stations; some good examples are [II.20, II.26]. Although these figures are quite variable over time, this estimation is key to let the decision makers know what the estimated amount of the investment they are facing is.

2.4.3.1. Introduction

When defining the elements of a hydrogen fueling station, we distinguish two main blocks: the elements common to any other “traditional” fueling station and those linked with production, use and dispensing of hydrogen, that is to say, those specifically required in this type of facility, due to the very nature of this fuel.

Among the elements common to any fueling station, be it gasoline or hydrogen, the civil work, electrical, mechanical and fire-fighting installations, and the necessary projects, studies and permitting processes to enable construction of the same are worthy of mention.

Among the elements a hydrogen fueling station requires to operate with this gas, we can list the hydrogen production block (if it produces the gas), compressors, filters, dispensing pumps and specific control systems.

It is worth noting that the larger the hydrogen fueling station is, that is to say, the higher the number of vehicles it can fuel daily is, the lower the specific weight of the “conventional” part is. Thus, in a small capacity fueling station, capable of fueling only a few vehicles a day, the conventional part might be 75% of the investment; on the contrary, in a large fueling station that can fuel a large average number of vehicles every day, the conventional part accounts for only 25% of the total investment.

In the following sections, the investment required for the different alternatives (technologies and sizes) is estimated, paying particular attention to various hydrogen production systems.

The figures given below are the result of contacts with equipment suppliers, providers and manufacturers, and the author’s experience in implementing projects related with hydrogen fueling stations in different technologies.

Instead of providing the range of possible values for the investment, indicating maximum, minimum and average values, we prefer to give our best estimate for the different alternatives, obtained from the specific calculation of what it would cost to develop some of these fueling stations in Andalusia.

2.4.3.2. Hydrogen fueling station with electrolyzer

In the case of electrolyzer-based hydrogen fueling stations, a study has been made of a configuration that includes a water tank, deionizer, electrolyzer, purifier, buffers, compressors, air dryer, filters and dispenser. The study started with small facilities, capable of fueling 40 to 60 vehicle fleets, and we noted the wide disparity in prices from one manufacturer to another; thus, for this same configuration, with the same conventional part, but with equipment from different manufacturers in the hydrogen part, there was a difference in prices ranging from one to two million euro for the total.

Therefore, considering the equipment from the manufacturers that offered a lower price, for a hydrogen fueling station with production slightly less than 25 kg/day, a cost of approximately one million euro can be established for a fueling station.

For larger fueling stations, increasing the capacity of the hydrogen part until it is capable of fueling more than 500 vehicles, and with three hydrogen dispensing pumps, the cost is 3.3 million euro, approximately, for a fueling station.

A summary of these configurations is provided in Table 2.3, where:

- Hourly production of hydrogen: expresses the production capacity for this gas, in cubic meters under normal pressure and temperature conditions, per hour.
- Daily production of hydrogen: expresses the daily total, reflected in kilograms.
- Fleet it can supply: is the number of vehicles in the fleet that fueling station would be able to fuel, assuming a daily consumption per vehicle of 0.6 kilogram of hydrogen.
- Dispensing pumps: expresses the number of hydrogen fuel pumps in the fueling station.
- Cost of the conventional part / hydrogen part: reflects the necessary investment in euro, as explained in 2.4.3.1.
- Total fixed cost or investment: is the sum of the two aforementioned columns.

Technology	Option	Hourly production / consumption of hydrogen (Nm^3/h)	Daily production / consumption of hydrogen (kg)	Fleet it can supply (vehicles) / dispensing pumps	Cost of the conventional part (€)	Cost of the hydrogen part (€)	Total fixed cost (investment) (€)
Hydrogen fueling station with electrolyzer	1	12.5	27	45 / 1	743,000	286,000	1,029,000
	2	16.0	34	57 / 1	743,000	720,000	1,463,000
	3	150.0	324	540 / 3	928,000	2,378,000	3,306,000
Hydrogen fueling station with reformer	1	4.5	9	15 / 1	743,000	555,000	1,298,000
	2	85.0	183	305 / 2	743,000	1,339,000	2,082,000
	3	170.0	367	612 / 3	928,000	2,497,000	3,425,000
Hydrogen fueling station without local production	1	15.7	34	57 / 1	743,000	114,000	857,000
	2	155.5	336	560 / 3	928,000	682,000	1,610,000

Table 2.3.- Estimated cost for different alternatives (technologies and sizes) in early stages

2.4.3.3. Hydrogen fueling station with reformer

Another option examined is the possibility of producing the hydrogen for the fueling station with a reformer, capable of converting other fuels (natural gas, bioethanol, etc.) into hydrogen in the necessary conditions.

Some examples of reforming reactions for hydrogen production include:

$$CH_4 + 2H_20 \rightarrow 4H_2 + CO_2,$$

in the case of natural gas (methane) being used as feedstock [II.27], or

$$CH_3CH_2OH + 3H_2O \rightarrow 6H_2 + 2CO_2,$$

in the case of ethanol (or bioethanol) being used as feedstock [II.28].

The configuration in this case is that of a water tank, a reformer integrated by several reactors, a purification system based on the pressure swing adsorption (PSA) process, buffers and hydrogen compressor, filters, air dryers and compressors, and hydrogen dispensing pumps.

Considering different options for the size of the reformer, and suiting the other components to the hydrogen flow, and even increasing the number of dispensing pumps from one (for the smallest fueling station) to three (for the largest), we obtain the result shown in Table 2.3.

2.4.3.4. Hydrogen fueling station without local production

The third configuration considered contemplates the hydrogen being delivered in some way to the fueling station. That is to say, it does not include the hydrogen generation part (although that of storage or that of dispensing is included); in particular, the elements considered for the non-conventional part are: buffers, dispensing pumps, compressor, dryer and air filters.

For different capacities of vehicles fueled daily, the figures, in this case, are shown in Table 2.3, where hourly consumption of hydrogen expresses the amount vehicles have refueled (in Nm^3) per hour, at each station, and daily consumption expresses the same (in kilograms) for 24 hours.

2.4.4. Cost of hydrogen fueling stations in the period 2020-2030

The fueling stations in the period 2020–2030 will mainly be of the "without local production" type, as each one will have to cover the requirements of 1,000 to 2,000 vehicles. These stations, larger in number of dispensing pumps and volume of civil work, will benefit, on the other hand, from expanded roll-out of the hydrogen economy, which will result, no doubt, in a lowering of the costs of different equipment (for example, hydrogen dispensing pumps or compressors).

Therefore, considering the current technology, and applying the discounts due to the experience curve and the economies of scale [II.29], we estimate that the cost of these fueling stations will be around €2,683,000 for the conventional part, plus €1,613,000 for the hydrogen part, totaling €4,296,000 per fueling station.

2.4.5. Estimate of the investment requirements

From the implementation strategy suggested in section 2.3, and considering the costs of the different possible hydrogen fueling stations that might be used to establish the infrastructure required (Sections 2.4.2, 2.4.3 and 2.4.4), the cost of the investment required for roll-out of the Hydrogen Economy in Andalusia, in the sector of motor land vehicles for the transportation of passengers, can be calculated.

From Table 2.2 we could try to assess a proposal of technologies implemented by stage, taking into account that not all the fueling station technologies are suitable for each stage of the roll-out process. At first, when there are few vehicles, fueling stations with a low roll-out cost must be sought; later on, when the number of vehicles increases, there will be gradual transition towards fueling stations with a cheaper price per kilogram of hydrogen. Table 2.4 would represent this proposal.

Year	Vehicles	Nodes	H_2 FS	Vehicles / FS (approx)	Technologies
2014	582	5	8	70	• 50% FS with electrolyzer • 50% FS with natural gas reformer
2015	1,196	8	16	80	• 50% FS with electrolyzer • 50% FS with natural gas reformer
2020	82,112	14	74	1,100	• 50% FS with natural gas and bioethanol reformer • 25% FS with electrolyzer with Ren.Energy • 25% FS with delivered hydrogen
2025	399,480	18	214	2,000	• 25% FS with natural gas and bioethanol reformer • 25% FS with electrolyzer with Ren.Energy • 50% FS with delivered hydrogen
2030	1,067,012	35	525	2,000	• 10% FS with bioethanol reformer • 15% FS with electrolyzer with Ren.Energy • 25% FS with delivered hydrogen • 50% FS with delivered renewable hydrogen

Table 2.4.- Technologies used in the roll-out

Also, within the roll-out, some of the infrastructure could be exploited for the construction of larger fueling stations, or with a more advanced technology.

Therefore, the investments to be made, grouped in 5-year periods, and considering the size and technology of each fueling station, are:

In the period:		Cumulative:
2014-2015:	€36.09 M	€36.09 M
2016-2020:	€181.58 M	€217.67 M
2021-2025:	€496.89 M	€714.56 M
2026-2030:	€1,336.06 M	€2,050.62 M

2.5. Conclusions

In this chapter, a procedure has been developed to allow the progressive identification of nodes and clusters in different stages in a region, to enable the roll-out of an adequate infrastructure of hydrogen fueling stations to go ahead. This procedure has been applied for the case of Andalusia, using as input the assessment of its municipalities obtained in a previous work.

The procedure allows defining precise roll-out strategies, leading to an estimation of not only the number of hydrogen fueling stations required, but also their size, nature or cost.

Its application has resulted in a roll-out process based on user nodes, whose numbers increase in order to let the penetration of hydrogen vehicles increase, and that benefits from their grouping in clusters.

The cost of migration to the hydrogen economy, and the necessary investment in aspects such as the roll-out of infrastructure, are also evaluated, and can be estimated with relative ease.

Moreover, the proposed systemized procedure prevents an inadequate roll-out of infrastructure (based on expediency or the existence of subsidies) that would lead to unnecessary cost and effort.

The information obtained from the application of this procedure will be useful to inform on the design of fiscal, economic or social policies that can promote migration to this new energy paradigm and, above all, to compare savings against the current, hardly sustainable, situation based on fossil fuels.

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CHAPTER THREE

ROLL-OUT OF HYDROGEN FUELING STATIONS IN SPAIN THROUGH A PROCEDURE BASED ON DATA ENVELOPMENT ANALYSIS

Abstract

Several automakers have expressed their intention to start commercializing hydrogen vehicles on a larger scale by 2015. This commercialization requires efficient roll-out of hydrogen fueling stations, with prior identification of the areas most suitable for their establishment. Suitability of the different areas will be determined by several supply and demand and environmental criteria. In this chapter, in the case of Spain, we apply a methodology based on Data Envelopment Analysis to select the appropriate municipalities for the establishment of hydrogen fueling stations in the early stages of the deployment process. This methodology has the advantage of reducing subjectivity in the criteria aggregation process for the selection of municipalities.

3.1. Introduction

On September 8, 2009, several of the world's leading automakers (Daimler, Ford, GM/Opel, Honda, Hyundai/KIA, the Alliance Renault/Nissan, and Toyota) signed a letter of understanding on the development and market introduction of fuel cell vehicles [III.1], in which they stated that: "Based on current knowledge and subject to a variety of prerequisites and conditions, the signing OEMs strongly anticipate that from 2015 onwards a quite significant number of fuel cell vehicles could be commercialized". In this same document, the signatories also stated that: "In order to ensure a successful market introduction of fuel cell vehicles, this market introduction has to be aligned with the build-up of the necessary hydrogen infrastructure", and indicated that a key criterion for the establishment of hydrogen fueling stations is that: "All hydrogen fueling stations are located smartly to enable customer access".

To plan this deployment of hydrogen fueling stations efficiently, some concept of suitability that enables identification of the most suitable areas for their establishment must be used. For us, there are two key features to this concept of suitability: it is not static, in the sense that it depends on the roll-out stage under consideration, and it is determined by several criteria.

The non-static nature means that it will depend greatly on the deployment process stage. Thus, areas deemed suitable for the establishment of hydrogen fueling stations during advanced stages of the roll-out process may not be considered as such in the early stages.

Even though the ideal areas can be selected based on a single criterion (mono-criterion), assimilating them, for example, to the number of actual vehicles in the different areas, the concept of suitability, from our viewpoint, must be defined more broadly by employing several criteria.

In general, these criteria can be classified into three main sets:

- *Demand criteria*: this set includes all the factors that influence the demand for hydrogen in a certain area. This demand will be determined both by the number of hydrogen vehicles owned in the area in question and by the number of hydrogen vehicles from other areas that transit in that area. In turn, the number of hydrogen vehicles owned in a certain area will depend on both the number of inhabitants and their willingness to use hydrogen vehicles. This willingness will in turn be influenced by the characteristics of these inhabitants (use of vehicle, age, income, level of education, level of environment awareness, etc.) [III.2-III.4]. Consideration of these criteria means that the degree of penetration of hydrogen vehicles in a city is not necessarily or exclusively proportional to the number of inhabitants.

- *Supply criteria*: this set of criteria refers to the potential impact of the technology used to produce hydrogen on the locating of hydrogen fueling stations. The production technology can determine the location of fueling stations in one area over another. For example, in a first stage, the hydrogen could be produced from natural gas. In this case, the absence of a natural gas network in the area could lead to the stations being located in another area with lower values in other criteria (such as demand), given the high cost of transport of hydrogen if the distance is far enough. Something similar occurs in the case of hydrogen production from renewable sources. The absence of renewable energy in an area means renewable hydrogen has to be transported from another area.
- *Environmental criteria:* one of the advantages of the Hydrogen Economy is the reduction in polluting gases caused by the use of fossil fuels in the transportation sector. This characteristic of hydrogen as an energy vector could lead the public sector, as a stakeholder in the deployment process, to value positively (and support) the location of hydrogen fueling stations in areas where there is too high a level of contamination, with the aim of promoting the use of a clean fuel in these areas.

These environmental criteria could also be included within the demand criteria. A higher level of contamination in one area could result in its inhabitants being more aware of environmental issues and, therefore, that there would be a higher demand for hydrogen vehicles in that area [III.2-III.4].

Multi-criteria approaches

The multi-criteria approach to the study of suitability has been applied in various studies. In [III.2], the authors study the geographical distribution of the demand for hydrogen vehicles to determine the location of hydrogen fueling stations in certain regions. These authors believe that the adoption by consumers of hydrogen vehicles is determined by several factors: household income, households with two or more vehicles, air quality, clean cities coalitions, commute distance, education, hybrid vehicle registrations, state incentives and Zero-Emission Vehicle Sales Mandate. These authors point out that not all attributes have the same influence on the demand for hydrogen vehicles. In this chapter, the weighing of the different criteria was performed by experts, and the values of the different attributes were divided into 5 categories arranged in order from the lowest (level 1) to the highest (level 5) influence on the demand for hydrogen vehicles. These considerations and weights were aggregated finally to estimate the demand for hydrogen in different areas within the regions studied.

HyWays [III.5] determines a series of early user centers and early hydrogen corridors for the 10 European countries participating in the project. In each participating country, 3 to 6 early user centers were identified from a qualitative evaluation of a list of regional indicators: local pollution, cars per household, size of cars, possibility for stationary use, availability of experts, existing demo-projects, favorable hydrogen production portfolio (renewable energy sources, by-product hydrogen), customer base, regional political commitment and stakeholder consensus.

Similarly, HyRREG [III.6] identifies a number of early user centers for Portugal, Spain and part of France. In the case of Spain, these were identified from a list of objective indicators developed and evaluated by the Capabilities Analysis Group of the Spanish Hydrogen and Fuel Cells Technology Platform (GAC PTEHPC), although the list of indicators is not provided in the reference. In the case of Portugal, 18 indicators (including those of HyWays) were used to assess 6 regions of Portugal; these indicators were evaluated by stakeholders on a 0 to 5 scale. Finally, in the case of France, no criterion for the selection of the early user centers is provided.

In Brey et al. [III.7], the authors used different criteria to determine the most suitable areas for the establishment of hydrogen fueling stations in Andalusia, a region of southern Spain. This region was divided into areas (770 municipalities) and each area was characterized in terms of 5 criteria. The criteria used were: number of vehicles registered, kilometers of national and regional roads, income per capita declared in each area, supply of renewable energies, and environmental pollution. Finally, based on interviews with experts and the use of the Analytical Hierarchical process, the aforesaid authors obtained a score for each municipality reflecting its suitability for the establishment of hydrogen fueling stations.

Aim of the study

The aim of this chapter is to plan the deployment of hydrogen fueling stations in Spain in an early stage. To this end, we characterize each of the 7,959 municipalities of mainland Spain in 2011 taking a series of criteria, presented in Section 3.2 hereof, into account. The purpose of these criteria is to reflect the suitability of each of the municipalities for the establishment of a hydrogen fueling station in an early stage. Finally, we use a procedure based on Data Envelopment Analysis to compare the different municipalities and select the suitable ones. The advantage of this technique is that it allows assessment of the suitability of municipalities without requiring excessive information from decision-makers, thereby reducing the subjectivity of the selection.

3.2. Proposed criteria for initial planning of the deployment in Spain

The setting for this study is an early stage of the transition to the hydrogen economy. Therefore, when determining the most suitable municipalities, we believe the most significant criteria to be those of demand, and we will focus only on the same. Supply criteria are only relevant in the sense that they establish some minimum conditions the municipalities must meet. Obviously, in the later stages of roll-out of the hydrogen economy, supply criteria will weigh more heavily.

We here-below detail the criteria used for this specific case study.

Supply criteria

- Availability of natural gas. In this chapter, we focus on planning the roll-out of hydrogen fueling stations in an early stage of the process. To this end, in line with several authors [III.8-III.13], we consider that the hydrogen would be produced by using steam methane reforming (SMR) in a more or less distributed way. Every municipality with available natural gas would decide to produce the hydrogen either "on site" at fueling stations, or in centralized SMR plants, distributing the hydrogen to near fueling stations. Thus, all the municipalities presently without a natural gas network are not taken into consideration. Only 1,373 municipalities have a natural gas network in 2012 on mainland Spain [III.14].
- Availability of a petrol station. Following the view of several authors [III.9, III.15], in the early stages of the process, and to reduce costs, the hydrogen would be supplied at fossil fuel fueling stations, resulting in these stations dispensing both fuels. This eliminates the municipalities without any gas station from the study. The number, in 2012, of municipalities on mainland Spain with at least one gas station, is 2,998 [III.16].

The application of these two criteria reduces the number of potentially suitable municipalities from the 7,959 existing municipalities of mainland Spain in 2011 to 1,104.

Demand criteria

- Number of vehicles. The number of vehicles can be interpreted as an indicator of the future demand for hydrogen vehicles in the different areas and, therefore, for hydrogen too. The number of vehicles in the different areas was obtained from [III.17] for the year 2011.
- Number of gas stations. The number of gas stations can be taken as an indicator of the demand for fuel in the different municipalities. An existing

higher demand for fossil fuel in a municipality means a higher future demand for hydrogen compared to other municipalities is more likely. The difference from the previous criterion is that this criterion also includes the demand generated by transit of vehicles between municipalities. The number of gas stations was obtained from [III.16].

- Average number of years of education of the residents. This criterion tries to capture the higher propensity to purchase hydrogen vehicles of the municipalities where there is a higher level of education. The average number of years of education by municipality was obtained from [III.18] for the year 2001.
- Number of financial institutions in the municipality. This criterion is included as a proxy variable for wealth in the municipalities[6]. The higher the level of wealth, the greater the propensity of the municipalities to be early-adopters of hydrogen vehicles. The number of financial institutions in Spain by municipality was obtained from [III.17] for the year 2011.
- Level of pollution. High levels of pollution from transport in a municipality can lead to an increased awareness of environmental issues in the municipality and, therefore, to a greater demand for hydrogen vehicles. However, in order for pollution levels to lead to this increase in demand for hydrogen vehicles, the pollution levels would have to be genuinely high.

In this chapter, we have considered pollutants derived from road transport with fossil fuels and for which there is a value legislated by the European Commission for the protection of human health. Thus, the pollutants taken into consideration are NO_2, PM10 y PM2.5. The pollution criterion used in this chapter for each municipality indicates the number of those pollutants that exceed the limit values for the protection of human health in 2011. The data were obtained from [III.19].

Table 3.1 shows the main descriptive statistics for the values of the demand criteria in the municipalities of mainland Spain that meet the supply criteria.

[6] The use of the variable "number of financial institutions" as a proxy for wealth was verified for the municipalities of Andalusia (a region in the South of Spain) in 2010, since for this particular case data were available.

	Number of gas stations	Number of vehicles	Average years of education	NO_2 and PM10 Pollution	Number of financial institutions
Minimum	1	103	5.17	0	0
Percentile 10	1	1,598	6.37	0	2
Percentile 30	2	3,626	6.99	0	4
Percentile 50	3	6,795	7.42	0	8
Percentile 70	4	12,618	7.94	0	14
Percentile 90	10	38,110	8.64	1	45
Maximum	176	1,924,383	10.65	2	2,981

Table 3.1.- Maximum and minimum values and 10^{th}, 30^{th}, 50^{th}, 70^{th} and 90^{th} percentiles for the values of the criteria in the municipalities

3.3. Selection procedure

The evaluation of municipalities based on a series of criteria can be done by weighing up the different criteria to obtain a single measurement that reflects the suitability of each municipality, i.e. associating, to each alternative (municipality in our case), an aggregate value of the evaluations obtained for the different attributes or criteria considered in the study. From this value, the ranking of the alternatives or the selection of a subset (considered the best) is immediate.

In the previous section, we have set the criteria and shown the values of each alternative against each criterion. If we assume that those values are aggregated in an additive way, all that remains is for us to determine which weight each criterion must have in the final value used to assess the alternatives. The allocating of weights to the criteria can be done by multiple procedures. Very briefly, these procedures can be classified into two major groups. On the one hand, those in which the weights result from the preferences expressed by one or more decision-makers on criteria (subjective weights). These types of weights would be those used in [III.7]. On the other hand, the procedures in which weights are obtained from the data itself, with the inclusion/consideration of technical or subjective constraints being possible when forming the weights (objective weights).

In this chapter, we propose a procedure for allocating weights that belongs to the latter of the aforementioned sets (objective weights). To be specific, we developed an assessment procedure based on Data Envelopment Analysis (DEA).

DEA is a non-parametric technique originally conceived to measure the efficiency of a set of units that obtain multiple inputs from multiple outputs

[III.20]. The aim of the original DEA models was to determine a measure of efficiency for each unit from the ratio of the weighted sum of the outputs over the weighted sum of the inputs. The weighting vector is freely selected for each unit so that each unit selects its own weighting vector, that with which it optimizes its own measure of efficiency, incorporating a set of constraints in the model that limits all the values of efficiency to the unit.

On the basis of this individual measure of efficiency, the units are classified as efficient (those that reach the maximum value of the ratio between outputs and inputs, equal to unity) and inefficient (the rest). Thus, if any unit is inefficient, this cannot be attributed to an arbitrary selection of the weighting vector.

The application of DEA models has far exceeded its original goals, generating a large number of models and procedures, all characterized by an endogenous selection of weights; the weighting vector is identified as a variable of the problem and not from the subjective preferences expressed by decision-makers.

However, DEA is not free from criticism. The main criticism focus on two aspects. On the one hand, the efficiencies of the different units are obtained using different weighting vectors. On the other hand, using these DEA models, multiple units are evaluated as efficient due to the flexibility in the selection of weights.

To solve these two problems, some authors have developed procedures based on DEA that enable attainment of a single weighting vector for all the alternatives [III.21- III.22]. These procedures are based on the idea that when the objective of the procedure is not the individual assessment of the alternatives but their comparison, it is more reasonable to evaluate all alternatives using the same weighting vector.

In this chapter, we propose a procedure for selecting alternatives based on this idea. This procedure maintains the essence of the DEA models, that is to say, determining the weighting vector objectively, as a variable of the model, but it assesses the set of alternatives using the same weighting vector.

Assume we have a set of n alternatives ($i = 1,\dots,n$) and we want to select a subset of e alternatives. For this purpose, we have k criteria ($j = 1,\dots,k$). In our case study, $n = 1{,}104$ and $k = 5$.

We denote by y_{ij} the value normalized to the interval [0, 1] the municipality i obtains as regards the criterion j. In our application, due to the existence of outliers, normalization of certain criteria (number of vehicles, gas stations and financial institutions) has been performed after substituting the values higher than the 97.5th percentile by said value, and the values below the 2.5th percentile by this value. This process is equivalent to assuming that for those criteria all the municipalities with a criterion value above (below) a specific threshold must be evaluated with the maximum (or minimum) value. This process in turn prevents the existence of a municipality or a few municipalities with a very high value in some criterion from prejudicing the assessment of the other municipalities in that criterion.

Each alternative is evaluated in terms of the weighed up sum of its values in each criterion, $\sum_{j=1}^{k} w_j y_{ij}$, where $w = (w_1, \ldots , w_k)$ is the weighting vector that assesses the criteria.

The weights to be used to select a set of *e* alternatives are obtained by solving the following constrained optimization problem:

$$
\begin{aligned}
\min \quad & F(d_i) \\
s.t. \quad & \sum_{j=1}^{k} w_j = 1 \qquad\qquad i = 1,\ldots, n \\
& \sum_{j=1}^{k} w_j y_{ij} + d_i \geq t_i D \quad i = 1,\ldots, n \\
& \sum_{i=1}^{n} t_i = e \\
& t_i \in \{0,\ 1\},\ w_j \geq 0
\end{aligned}
\qquad \text{Eq. [3.1]}
$$

In Eq. [3.1] the variable d_i is a variable of distance or deviation to a sufficiently large arbitrary maximum *D*. We denote by $F(d_i)$ the assessment measurement of the subset of *e* alternatives we want to select. The simplest measurement is to consider the sum of individual deviations, but other alternative measurements such as the maximum deviation or a weighed up sum could also be considered. The t_i variables are binary variables that take the value 1 when the corresponding alternative *i* is selected in the subset of *e* alternatives. Only the selected alternatives, those with a value equal to 1 in the t_i variable, affect $F(d_i)$. In the cases in which $t_i = 0$, the second set of constraints is redundant and, therefore, the value of d_i will be 0.

The solving of Eq. [3.1] allows determining of the weighting vector and the set of *e* alternatives that minimizes the sum of the d_i deviations and, therefore, maximizes the overall evaluation of the subset. It is interesting to note that, even though only selected units affect the value of the objective, all the units affect the selection of the weights, as they are all considered in the first set of constraints that limit the aggregate value to the unit.

Incorporating additional information

The solving of Eq. [3.1] can sometimes lead to the attainment of extreme solutions, i.e. weighting vectors in which one or several components are null. Furthermore, the weighting vector obtained, although determined in an objective way, may be far from the preferences of decision-makers on the criteria. To avoid these two drawbacks, it is advisable to incorporate additional information on the weights in Eq. [3.1].

This additional information can be used to establish an interval to the value of each component of the weighting vector. This can be achieved by including constraints of the $b_j \geq w_j \geq a_j$ type, where a_j and b_j represent the limits of the interval. Similarly, constraints on the participation of each criterion in the aggregate value can also be included, i.e. establishing an interval of possible values to the $w_j y_{ij}$ products.

In this way, we reduce the flexibility characteristic of the initial DEA models, by placing limits on the values of the weighting vector. However, we manage to get some weights that are determined endogenously by the model in Eq. [3.1] and also incorporate the preferences of the decision-makers.

In this chapter we incorporate, into the model, information on the preferences of decision-makers gathered through a survey of experts in this field. We asked each expert to allocate 100 points among the 5 criteria on the basis of their relative importance for the establishment of a hydrogen fueling station.

As expected, the experts did not coincide in their evaluations, so it was not possible to obtain a single weighting vector. However, their responses enabled the setting of limits to the values of the components of the weighting vector (see Table 3.2).

Criterion	Min	Max
Number of conventional gas stations	15	40
Number of register vehicles	20	30
Number of financial institutions	5	25
Average years of education	10	30
Contamination level	10	25

Table 3.2.- Weights of the experts

With the information shown in Table 3.2 and solving Eq. [3.1] for subsets of 20, 30 and 50 municipalities (e = 20, 30, 50 and 100), we obtained three weighting vectors and the municipalities selected in each subset. In the three cases, we obtained the same weighting vector. This weighting vector is shown in Table 3.3. The municipalities selected for each of the three cases considered are presented in Section 3.4.

Criterion	
Number of conventional gas stations	0.35
Number of register vehicles	0.20
Number of financial institutions	0.10
Average years of education	0.25
Contamination level	0.10

Table 3.3.- Weighting vector

3.4. Results

The application of the proposed procedure based on DEA has allowed us to obtain, using the different criteria and the weights allocated by experts, sets of municipalities. Specifically, we have considered sets of 20, 30, 50 and 100 municipalities. The selected municipalities are shown in Figure 3.1.

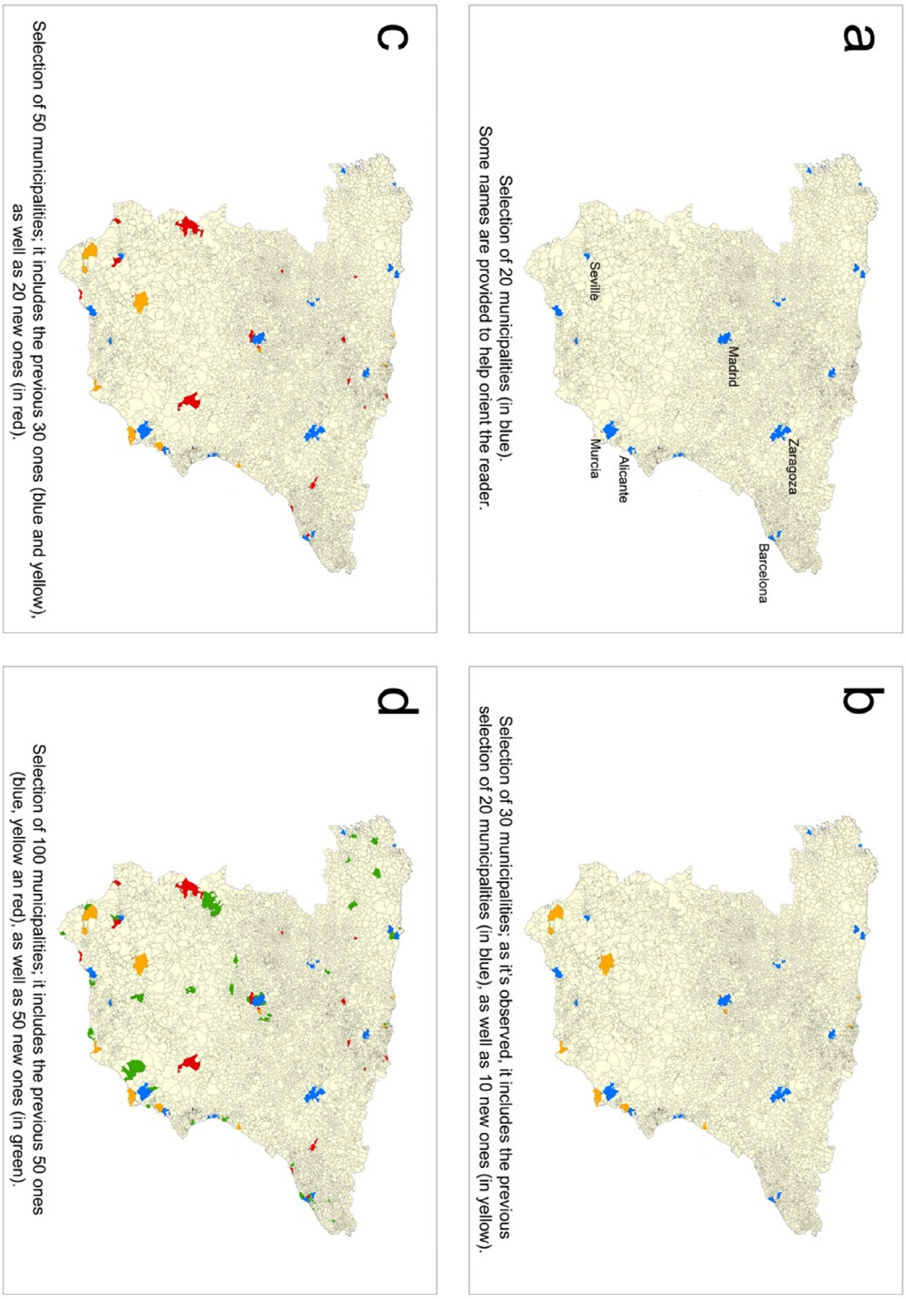

Figure 3.1.- Sets of 20 (a), 30 (b), 50 (c), and 100 (d) municipalities selected (grey boundaries indicate Spanish municipalities)

Let's remember that the practical concern of the proposed procedure is the selection of municipalities to start the roll-out of hydrogen fueling station infrastructure in Spain in different time stages. Therefore, the fact that, in the results obtained, the 20 municipalities of the first set are included in the 30 of the second set, and so on successively, is a hugely positive aspect as it allows us to undertake coherent step-by-step roll-out of the infrastructure in Spain. This consistency in the progressive deployment of the infrastructure is due to the fact that, as mentioned earlier herein, the solving of model in Eq. [3.1] with the constraints on the weights of the criteria established by the experts, has provided the same weighting vector.

Geographically analyzing the results, we also see a certain tendency that facilitates the design of the roll-out strategy. We can identify three major geographical areas that could be considered clusters (see, for example, [III.23]) or favored development zones. These zones are the north of Spain, the center of the Iberian Peninsula and the Mediterranean coast.

These results are broadly in line with those obtained by the HyWays project [III.5], while showing more differences with the regions identified in [III.6] for Spain, as the latter project does not identify the Mediterranean coast as a favored development zone.

Finally, an analysis must be made of whether the results obtained in a multi-criteria process like this one are similar to, or even exactly the same as the results we would have obtained when considering only one of the criteria.

If we considered only one of the demand criteria, in isolation, to select the municipalities we could obtain, at best, a similar result, but not one equal to that obtained with our method. This is only logical if we consider we have used demand criteria chosen with a certain sense of coherence.

However, the differences, and not the similarities, are what matter in the results. The multi-criteria analysis used in this study presents variations in the lists of selected municipalities compared to the results obtained when a single criterion is used. For example, when comparing with the results obtained when the two criteria most highly valued by the experts (number of gas stations and number of vehicles) are used separately for the case of 30 selected municipalities, we obtain differences of 20-30% in the results. We believe these differences are significant enough to merit an analysis such as that suggested in this chapter.

3.5. Conclusions

In the coming years, the major automakers intend to start commercializing hydrogen vehicles on a larger scale. The successful introduction of these hydrogen vehicles in the market will depend, to a large extent, on a suitable network of fueling stations for these vehicles.

The establishment of this network must necessarily be done gradually, locating the stations in the areas deemed most suitable. In this chapter, we have defined this concept of suitability based on different criteria, and we have used a procedure based on Data Envelopment Analysis (DEA) to select the most suitable municipalities for the establishment of hydrogen fueling stations on mainland Spain in the early stages of roll-out. This procedure allows obtaining of weights for the different criteria that are determined endogenously by an optimization model and which also incorporate the preferences of decision-makers.

Anyway, as mentioned at the beginning of this chapter, the concept of suitability is not static; therefore, these selected criteria are contingent on the roll-out stage under consideration, and, under a different scenario (for example, time or place), other criteria could be selected by the experts.

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CHAPTER FOUR

A DEA BASED PROCEDURE FOR THE SELECTION OF SUBGROUPS

Abstract

Data Envelopment Analysis (DEA) is a non-parametric technique originally conceived for efficiency analysis of a set of units. The main characteristic of DEA based procedures is endogenous determination of weighting vectors, i.e., the weighting vectors are determined as variables of the model. Nevertheless, DEA's applications have vastly exceeded its original target. In this chapter, a DEA based model for the selection of a subgroup of alternatives or units is proposed. Considering a set of alternatives, the procedure seeks to determine the group that maximizes overall efficiency. The proposed model is characterized by free selection of weights and allows the inclusion of additional information, such as agent's preferences in terms of relative importance of the variables under consideration or interactions between alternatives. The solution is achieved by computing a mixed-integer linear programming model. Finally, the proposed model is applied to plan the deployment of fueling stations in the province of Seville (Spain).

4.1. Introduction

DEA [IV.1] is a non-parametric technique originally conceived to measure the efficiency of a set of units that produce multiple outputs with multiple inputs. The original models seek to determine individual efficiency measurements for each unit by the ratio of the weighted sum of outputs over the weighted sum of inputs. The weighting vectors are freely selected by each unit or DMU (Decision Making Unit) in DEA terminology, i.e., each unit can select the vectors of weights so its own efficiency measurement is optimized, with a common set of constraints that limit this value usually to be equal or lower than the unity. Therefore, each DMU can select its own vector of weights to optimize its individual efficiency measurement. Hence, if a unit does not achieve the maximum value, it cannot be attributed to an arbitrary selection of the weighting vector.

This model classifies alternatives into two categories: efficient alternatives, i.e., those ones which achieve the maximum value of the ratio, and non-efficient, all others. In the latter case, the difference with the unity represents a measure of inefficiency.

The application of DEA models has vastly exceeded its initial objectives, generating a huge number of models and procedures, all characterized by endogenous selection of weights. That is, the weighting vector is determined as a variable of the problem and not externally fixed by the decision makers.

There are two main reasons for criticism of DEA models. On one hand, the efficiencies of different DMUs are obtained by considering different sets of weights. Therefore, comparisons between alternatives and rankings cannot be made on the same basis. Several authors have pointed out that fair comparisons are not possible using individual vectors for alternatives (see, among others, [IV.2] and [IV.3]).

On the other hand, flexibility in the selection of weights very often results in multiple alternatives being evaluated as efficient. This implies that the set of DMUs cannot be fully discriminated and, therefore, a full ranking of alternatives cannot be obtained. In this context, when the objective of the model is to compare between units or to construct a ranking, it would be inappropriate to use different vectors for the evaluation of the alternatives.

In order to solve these two problems, several procedures have been developed which attempt to provide a unique set of weights for all units. These proposals can be divided into two groups: cross-efficiency models and common-weight procedures.

The initial proposal is cross-efficiency evaluation [IV.4]. In this paper, the authors proposed to evaluate each unit not only using its optimal vector of weights but also the optimal vectors of the remaining units. In [IV.5] is shown that this evaluation concludes with the generation of a fixed set of weights.

A second family of procedures based on the determination of a common set of weights is originated by the proposal in [IV.6]. These models determine, in a first stage, a target value for each unit, which usually coincides with the individual evaluation of the unit (the one obtained with traditional DEA-models). In a second stage, a common vector of weights is obtained that minimizes the gap between the evaluation of the alternatives and its target value. This group of procedures includes most notably [IV.7] - [IV.9]. Nevertheless, the essence of DEA-models is kept since the weighting vector is obtained as a part of the model.

This chapter proposes a DEA based model for selecting a subgroup of alternatives. The main idea is the development of a common-weight procedure that allows determining the best subgroup of alternatives from a given set, in such a way that the overall efficiency of the selected group is optimized. It is important to bear in mind that overall evaluation of the group, and not the individual evaluation of the selected alternatives, is the objective.

Some DEA based models focus on the idea of selecting alternatives; for instance, models related with location problems and models for the selection of the best alternative. The former incorporate the objective of maximizing efficiency into the classical objectives of location problems. Examples of these models are [IV.10], where the authors propose to solve an efficiency measure simultaneously with the objectives of the classical location models, and [IV.11], where the authors develop the previous ideas for a multicriteria and fuzzy context. On the other hand, models for selecting the best alternatives try to break ties among efficient alternatives in order to determine which one is the best valued. Some examples are: [IV.12], where the most efficient alternative is determined in presence of both cardinal and ordinal data; [IV.13], where the best alternative is determined by maximizing the lower bound of the weighting factors; [IV.14], which proposes a procedure to determine the best alternative when a model with constant return of scale is considered; [IV.15], which develops [IV.14] for the case of the variable return of scale model; and [IV.16], which presents an improved version of the model proposed in [IV.15]. In all these cases, the authors aim to determine the best unit by computing only one model, and not by considering iterative processes. Moreover, in most of them, mixed-integer linear programming models are developed.

None of the aforementioned works propose a global measure of efficiency for the selected group, as all consider individual evaluations. A new procedure for the selection of subgroups is proposed in the following sections. Although all the alternatives play a role in determining the optimal weighting vector, the selected alternatives alone are considered to compute the subgroup's efficiency value.

The connection between DEA and multicriteria procedures proposed in [IV.17] is used to describe the model. In this chapter, the authors develop traditional DEA-models from a multicriteria perspective, including novel objectives for measuring DMUs efficiency. In particular, minisum, minimax and compromise values between them, are studied. Moreover, the inclusion of additional information is considered.

The rest of the chapter is organized as follows. Section 4.2 presents and describes the model and its main features. Section 4.3 focuses on the inclusion of additional information into the basic model. Section 4.4 includes a numeric application of the proposed model, studying the location of a set of hydrogen fueling stations in the province of Seville, in the south of Spain. Section 4.5 summarizes the main conclusions.

4.2. A model for the selection of subgroups

Let us consider a set of n alternatives from which a subgroup of e units, with $e \leq n$, must be selected. Each alternative is evaluated with respect to different variables and the aggregated evaluation used in DEA-models. The goal is to create a model in which only the selected alternatives are computed to measure the overall evaluation of the subgroup, whereas all the alternatives are considered to determine the optimal weighting vector. Several applications fit into this framework. Consider, for example, location problems in which a network of new sites must be selected from multiple possibilities, or design problems for optimal project portfolio. In both cases, the selection of a subset of units is required. The objective is to optimize the joint evaluation of the selected group, rather than maximize individual evaluations.

The main features of the proposed model are summarized below:

- A model with free weight selection. A DEA based procedure is studied in which the weighting vector is endogenously determined.
- A common-weight model. The proposed procedure evaluates all units using the same set of weights to try to facilitate the comparison of alternatives and avoid the existence of multiple level-pegging alternatives. The idea of valuing the subgroup as a whole (not the sum of individual entities) justifies the use of a common set of weights to evaluate all selected alternatives.
- Alternative objectives. A multiple criteria decision making analysis is used to study the common-weight DEA model. The proposed procedure allows different objectives to be considered when measuring the performance of the selected group. In particular, the sum of individual performances and the minimax measurement will be studied.

The notation introduced in [IV.17] is considered to describe the model. In this chapter, the author point out the links between DEA and multicriteria analysis, rewriting DEA models on the basis of deviation variables.

Let us consider a general problem in which *n* units or alternatives are evaluated with respect to *p* inputs and *m* outputs. We denote respectively by x_{ir} and y_{is} the quantities used of input *r* ($r = 1,\ldots,p$) and produced of output *s* ($s = 1,\ldots,m$) by the unit *i* ($i = 1,\ldots,n$). The original model, proposed in [IV.1], evaluates the efficiency of unit o by computing the following model:

$$
\begin{aligned}
\max \quad & \sum_{s=1}^{m} w_{os} \cdot y_{os} \\
\text{s.t.} \quad & \sum_{r=1}^{p} u_{or} \cdot x_{or} = 1 \\
& \sum_{s=1}^{m} w_{os} \cdot y_{is} - \sum_{r=1}^{p} u_{or} \cdot x_{ir} \le 0, \quad \forall i \\
& u_{or}, w_{os} \ge \varepsilon, \quad \forall r, s,
\end{aligned}
\qquad \text{Eq. [4.1]}
$$

where w_o and u_o denote the weighting vectors of outputs and inputs respectively, and ε denotes a non-archimedian infinitesimal included to guarantee the existence of an optimum (see [IV.18] for discussion on this). Note that this model computes a particular vector for the DMU under evaluation (DMU o). Therefore, model in Eq. [4.1] must be solved *n* times to evaluate the set of alternatives, obtaining an optimal vector of weights for each alternative. As proposed in [IV.17, IV.19], this model can be rewritten using deviation variables d_i:

$$
\begin{aligned}
\min \quad & d_o \\
\text{s.t.} \quad & \sum_{r=1}^{p} u_{or} \cdot x_{or} = 1 \\
& \sum_{s=1}^{m} w_{os} \cdot y_{is} - \sum_{r=1}^{p} u_{or} \cdot x_{ir} + d_i = 0, \quad \forall i \\
& u_{or}, w_{os} \ge \varepsilon, \quad \forall r, s.
\end{aligned}
\qquad \text{Eq. [4.2]}
$$

In Eq. [4.1], the efficient units are identified by a value equal to the unity. In Eq. [4.2], the efficient units achieve a null value of the corresponding deviation variables. It is easy to see that both results are equivalent. The optimal value of d_o, included in the interval [0,1], provides a measure of the inefficiency of unit o. Using the notation introduced in Eq. [4.2], Li and Reeves [IV.17] reconsider the model from a multicriteria perspective (Eq. [4.3]), allowing additional objectives to be considered for optimization of individual efficiency d_o, such as the objectives of minisum (which optimizes the sum of individual efficiencies of n DMUs, $\sum_{i=1}^{n} d_i$) and minimax efficiency (which optimizes the efficiency of the worst DMU, which can be computed through variable D).

$$
\begin{aligned}
&\min && d_o \\
&\min && D \\
&\min && \sum_{i=1}^{n} d_i \\
&s.t. && \sum_{r=1}^{p} u_{or} \cdot x_{or} = 1 \\
& && \sum_{s=1}^{m} w_{os} \cdot y_{is} - \sum_{r=1}^{p} u_{or} \cdot x_{ir} + d_i = 0, \quad \forall i \\
& && D - d_i \geq 0, \quad \forall i \\
& && u_{or}, w_{os} \geq \varepsilon, \quad \forall r, s.
\end{aligned}
\qquad \text{Eq. [4.3]}
$$

This model is taken as the starting point for the group selection procedure proposed in this chapter. A common-weight model can be developed using Eq. [4.3], eliminating the objective of optimizing the individual efficiency of each alternative. The following model is specifically developed for a pure-output model, in which alternatives are evaluated only with respect to output variables. The study of this case is justified by the aforementioned application.

Let us assume that each unit produces multiple outputs using a single, common input. The production of output s ($s=1,\ldots,m$) of unit i ($i=1,\ldots,n$) is denoted by y_{is}. Each alternative is evaluated on the basis of the aggregate value of outputs $\sum_{s=1}^{m} w_s \cdot y_{is}$, with $w = (w_1,\ldots,w_m)$ denoting the common vectors of weights associated to the outputs.

The traditional normalization constraint of the DEA model is substituted by a condition such that the aggregate value $\sum_{s=1}^{m} w_s \cdot y_{is}$ is lower that the unity for all $i=1,\ldots,n$. Alternative forms could be considered for this constraint (for example, a normalization constraint over the weighting vector w). With this constraint, the efficient alternatives are identified as those achieving an aggregate value equal to 1. To identify the alternatives finally selected, a set of binary variables t_i is included. A value of t_i = 1 denotes that alternative i is selected.

Considering the notation introduced, the model for selecting the best subgroup of e alternatives from a set of n alternatives is proposed below.

$$\begin{aligned} min \quad & F(d_i) \\ s.t. \quad & \sum_{s=1}^{m} w_s \cdot y_{is} \leq 1, \quad i = 1,\ldots,n; \\ & \sum_{s=1}^{m} w_s \cdot y_{is} + d_i \geq t_i, \quad i = 1,\ldots,n; \\ & \sum_{i=1}^{n} t_i = e, \\ & t_i \in \{0,1\}, w_s \geq \varepsilon. \end{aligned} \qquad \text{Eq. [4.4]}$$

Similarly to the proposal of Eq. [4.2], deviation variables d_i measure the distance to the maximum aggregate value of outputs, set at 1 in Eq. [4.4]. Unlike the DEA based assignation models (see, for example, [IV.20]), in this case the selection of a subgroup of alternatives is the primary objective. The set of alternatives is divided into two groups: selected and non-selected ones. Only the efficiency of selected alternatives will compute in terms of the objective function.

Objective function $F(d_i)$ represents a distance function that computes the efficiency of the selected subgroup. Different concepts of *global efficiency* can be considered when this function is included in the model. The final choice will depend on the analyst's preferences or the context of the problem to be solved. The minimization of the summation of deviation variables (minisum), $F(d_i) = \sum_{i=1}^{n} d_i$, and the minimization of the maximum (minimax solution), $F(d_i) = \max_{i=1,\ldots,n}\{d_i\}$, are considered in this chapter. Both cases allow obtaining a linear expression of the objective function. The former is immediate and the latter is obtained by including a set of constraints such that $D \geq d_i$, $\forall i = 1,\ldots n$ and the minimization of the variable D. Compromise solutions may be examined, such as those proposed in [IV.16], to discriminate among multiple solutions and complement basic solutions. Unlike the proposal of Eq. [4.3], a multiobjective model is not proposed in this chapter as the two objectives are not simultaneously optimized. Note that only the objectives that best fit with the target of the procedure are considered here: to maximize the total efficiency of the selected subgroup, and to maximize the minimum efficiency of the selected subgroup. In addition, both objectives (minisum and minimax solutions) allow construction of a linear approach.

The first set of constraints in Eq. [4.4] guarantees that the aggregate value of each unit is bounded by the unity. It is interesting to note that all the alternatives, whether finally selected or not, play a role in the determination of the optimal vector of weights through the bound of the aggregate value. However, only the selected units will be considered to compute the efficiency of the subgroup.

To understand how the model works, the second set of constraints must be studied. If t_i = 0 (that is, alternative *i* is not selected), the corresponding restriction is redundant. It should be noted that since all variables are non-negative, the constraint could be verified by assigning any non-negative value to d_i. However, a zero value for d_i will be assigned because the objective function aims at minimization of these deviation variables.

Likewise, if t_i = 1, the restriction is active, since the aggregate values have to achieve the ideal value (equal to the unity). In that case, either the aggregate value achieves the maximum value, or a certain value must be assigned to the corresponding deviation variable d_i. The minimization objective guarantees that only the best *e* alternatives are selected, that is, those that assign the minimum values to variables d_i, in order to minimize the deviation variables for the set of selected alternatives. Note that for all the alternatives that are not selected, a zero value will be assigned to their corresponding d_i, regardless of whether they are efficient or not.

The third constraint assures that the previously set number of alternatives *e* is selected. A simple variation of the basic model would enable determining of the maximum number of efficient alternatives to be selected, if some limitations are imposed on feasible combinations of alternatives.

It can be seen that model in Eq. [4.4] is feasible for any value of *e*. Once the values are assigned to the binary variables t_i, model in Eq. [4.4] becomes a goal-programming model, where d_i are deviation variables that measure the distance of the aggregate value to the target value for the selected alternatives. This feature, combined with the non-negativity of the variables, and the normalization constraint for vector *w*, guarantees the feasibility of Eq. [4.4]. For example, if *e* = *n*, the model will select the complete set of alternatives, being therefore equivalent to the one proposed by [IV.15] which considers a common set of weights.

The selection of a particular alternative only implies that its deviation variable is included in the objective function, but not that the selected alternative is necessarily an efficient one. The aim of this model is not to determine a set of *e* efficient alternatives. The subset of the selected *e* alternatives usually will contain both efficient and inefficient alternatives.

If the optimal value of the objective function is reached by more than one set of *e* alternatives (for example, if the number of efficient alternatives exceeds the value of *e*, having in this case the objective function an optimal value of zero), multiple combinations of units could be selected. In this case, the inclusion of additional information or other procedures should be contemplated to discriminate among multiple solutions, for example, applying, additional procedures over the initial DEA model (see [IV.21]) or adapting specific procedures for the common-weight context (see [IV.22]). These discriminating procedures could be carried out in a second stage, taking the form in which the model has been constructed into consideration: common weighting vector, selection of a subgroup of alternatives…

The following Section focuses on the inclusion of additional information into the model in Eq. [4.4]. This additional information could be used not only to discriminate when alternative optimal solutions are obtained (as aforementioned), but also to capture better decision makers' preferences if true information about preferences on the relative importance of variables, or about restrictions on feasible combinations of alternatives, is available. In any case, a linear expression will be obtained to preserve the linearity of the model.

4.3. Incorporating additional information

This section examines the inclusion of additional information into basic models. The main characteristic of DEA based models is the free selection of weights, with only some constraints to ensure an appropriate value for the weighting vector. Nevertheless, in that case in which true information about the relative importance of variables exists, it must be included in the model, while preserving the philosophy inherent in DEA procedures.

4.3.1. Additional information about weights

The inclusion of restrictions on feasible weight values has been widely studied in DEA literature. Several papers propose the incorporation of additional constraints to the components of the vector of weights which, although conceived for traditional DEA models with individual weighting vectors, may be easily adapted to common-weight DEA models.

In this case, the values assigned to each variable can be modelled by including absolute bounds to the components of *w*, or relationships among those components, or relationships among virtual values (products of $w_s \cdot y_{is}$). For a detailed study refer, inter alia, to the works of [IV.23] - [IV.25].

4.3.2. Additional information about the feasible combinations of alternatives

In addition to the restrictions on the feasible values for the components of weighting vector *w*, this model also contemplates limitations on the pairs of alternatives that can be selected. The idea is to include in the model restrictions that enable to express interactions between pairs of alternatives, incorporating into the model situations in which, for example, two alternatives cannot be selected simultaneously, or the selection of an alternative necessarily implies the selection of another. The first case considers, for example, a location problem in which several locations must be selected from a group of feasible ones. In this case, the avoidance of the closest locations (in order to cover a larger area) or the most distant (for a logistic purpose) is logical.

Let us suppose that alternatives *i* and *j* are linked in such a way that both alternatives should not be selected simultaneously. There is no objection to selecting *i* or *j* separately, or neither. The restriction only arises when both alternatives are included in the selected subgroup of the best *e* values.

In order to identify mutually excluding alternatives, i.e., alternatives that cannot be selected simultaneously, a binary matrix *A* is considered, such that,

$$a_{ij} = \begin{cases} 1 & \text{if alternatives } i \text{ and } j \text{ are mutually excluding alternatives,} \\ 0 & \text{otherwise.} \end{cases} \quad \text{Eq. [4.5]}$$

To identify the existence of a conflict, i.e., both alternatives are selected, the following set of constraints is considered,

$$\begin{aligned} & t_i + t_j - \alpha_{ij} \leq 1, \forall i \neq j, \\ & \alpha_{ij} \in \{0,1\}. \end{aligned} \quad \text{Eq. [4.6]}$$

By Eq. [4.6], the alternatives are compared by pairs through their corresponding binary variables t_i. The assignment of values to variable α_{ij} is summarized in Table 4.1.

Selection (pair i and j)	t_i	t_j	α_{ij}
Alternatives i and j	1	1	1
Alternative i	1	0	0
Alternative j	0	1	0
Neither i nor j	0	0	0

Table 4.1.- Values of variable α_{ij}

To ensure the selection of the non-conflicting pairs, the following set of restrictions is included

$$\alpha_{ij} \cdot a_{ij} = 0, \forall i \neq j. \quad \text{Eq. [4.7]}$$

It is clear that Eq. [4.7] is only active for those pairs in which $\alpha_{ij} = 1$ and $a_{ij} = 1$ occurs simultaneously. In other cases, the constraint is redundant. It is worth noting that this set of constraints can make the problem infeasible. If the number of limitations for feasible pairs of alternatives is large, it could reduce the number of feasible alternatives to a value lower than *e*, in which case the problem would have no solution.

Synergies can be modelled for alternatives with a similar set of constraints. The benefit derived from the selection of a particular pair of alternatives can be quantified using a similar procedure. In this case, cardinal values (measurement of the benefit) or binary values (the benefit exists or not) can be considered.

A second class of limitation represents a situation where the selection of a particular unit *i* serves no purpose if alternative *j* is not also selected. Consider, for instance, a project portfolio problem where implementation of project *i* is only possible if project *j* is also executed.

Let us consider a matrix *C* as follows,

$$c_{ij} = \begin{cases} 1 & if\ unit\ i\ depends\ of\ unit\ j, \\ 0 & otherwise. \end{cases} \quad \text{Eq. [4.8]}$$

Several aspects of matrix *C* are noteworthy. Unlike matrix *A*, matrix *C* is not necessarily a symmetric matrix. If alternative *i* requires prior selection of *j*, this does not mean that *j* cannot be individually selected. In fact, when $c_{ij} = c_{ji} = 1$ both alternatives can only be jointly selected (or, obviously, unselected).

In order to guarantee the selection of the alternatives in proper form, the following set of constraints must be included.

$$(t_j - t_i) \cdot c_{ij} \geq 0, \forall i \neq j. \qquad \text{Eq. [4.9]}$$

Where i can only be selected jointly with *j*, this is represented by $c_{ij} = 1$ (and $c_{ji} = 0$), and implies that $t_j \geq t_i$. If both alternatives have to be jointly selected, this is noted by $c_{ij} = c_{ji} = 1$, which implies that $t_i = t_j$.

4.3.3. Extensions on the basic problem

So far, the proposed procedure has attempted to select a fixed number of best-suited alternatives, with the features described above, from a larger set of units. In every case, *e* was considered a parameter with a pre-established value. Certain modifications to the proposed model will allow other problems to be addressed.

Let us suppose that the optimal number of alternatives is yet to be determined. In this case, there are two possible situations. If there are no limitations regarding the number of alternatives that may be selected, the objective of maximizing overall evaluation of the group is meaningless. Given that all alternatives have a nonnegative evaluation, if the objective is getting the highest sum possible for the evaluations, then, the procedure will select all the alternatives and the *optimal* value of *e* shall be *n*. In this case, alternative objectives such as maximization of average evaluation, equivalent to the determination of the number of efficient alternatives, may be considered. If there are limitations to feasible alternatives, the objective of maximizing the overall evaluation of the selected subgroup can be included to compute the optimal value of variable *e*.

Other extensions can be studied considering the proposed procedure. Consider, for instance, the creation of a subgroup from a particular alternative. This situation can be easily implemented including a restriction such that $t_o = 1$, where o is the alternative previously selected. Note that this feature brings a double implication. On one hand, the combinations of alternatives must be compatible in all cases with the selection of alternative o (in those cases where limitations on feasible pairs exist). On the other hand, the optimal vectors of weights must give a high score to the previously selected alternative, as well as to all other e - 1 alternatives selected.

4.3.4. Numeric application: obtaining an optimal distribution of hydrogen fueling stations

In a recent paper [IV.26], the authors studied the creation of a network of hydrogen fueling stations in Andalusia (Spain), selecting the best-suited municipalities for the establishment of hydrogen fueling stations. The authors utilized the Analytical Hierarchy Process to rank the municipalities, based on multiple performance evaluation criteria in terms of supply, demand and environment. However, when it is not possible to reach a consensus among the decision-makers, or non-subjective weighting vectors are to be obtained, the utilization of DEA is especially suited. By way of an example, DEA is applied in this chapter to study infrastructure deployment in the transition to hydrogen economy.

In the hydrogen economy, this gas will be used as a fuel in place of traditional fossil fuels to feed different transport vehicles. However, the way in which the transition to this economy will be effected continues to be under discussion. It is clear that the shift from the current energy paradigm to a new one will be neither easy nor cheap.

A major part of the investment will go towards building infrastructure. For hydrogen to be used as an energy carrier, vehicles should readily access hydrogen. To that end, an appropriate network of fueling stations must be available.

The optimization of infrastructure deployment is critical to make the transition possible. While a weak investment strategy could make impossible a smooth transition, an exceedingly ambitious strategy could be impossible to achieve.

In this section, the proposed procedure is applied to the planning of the deployment of hydrogen fueling stations in the province of Seville, in Spain. Out of its 104 municipalities, the best subgroup is selected with an optimized overall evaluation.

To that end, each municipality was characterized by the following 6 criteria (a more detailed explanation is provided in [IV.26]):

- Demand criteria. The municipalities with most likely potential hydrogen buyers were identified using this criterion. The evaluation of a unit with a better performance in this criterion would be higher. Three sub-criteria were considered:

- Number of registered vehicles. The assumption is that the higher the number of vehicles, the greater the demand for fuel and, consequently, for hydrogen. The number of vehicles registered in 2008 was recorded for each municipality.
- Kilometres of national and regional roads. Municipalities with the most kilometres of roads are more likely to have a higher demand for fuels in general, and hydrogen in particular. This criterion seeks to take into account traffic volume in each municipality.
- Income per capita. Hydrogen vehicles will be more costly than traditional vehicles. Therefore, it is more likely that demand for this type of vehicles will come from municipalities with higher incomes.

- Supply criterion: renewable energies. The chapter considers the production of hydrogen from renewable sources. In order to minimize hydrogen transportation cost, the procedure prioritizes availability of renewable energies (biomass, solar, wind and small hydro) in the municipality.
- Environmental criterion. Each municipality is characterized by its pollution level. Municipalities with high pollution levels could become early adopters of pollution-free technologies like hydrogen. Greenhouse gases have been taken into consideration and converted into tons of CO_2 equivalent.
- Number of gas stations. The higher the number of gas stations available in the municipality, the easier to set up a new hydrogen fueling station (for complementary or substitutive supply).

All referred variables verify that *more is better*, hence subgroup is selected by computing the model in Eq. [4.4]. That is, a set of 104 DMUs have been considered, with every feasible location characterized by 6 variables (considered as problem outputs). Table 4.2 summarizes the main values of the variables.

	Average Income (€)	*Road network (km)*	*Number of motor Vehicles*	*Gas stations*	*Environmental Pollution ($t\ CO_2$ eq.)*	*Renewable energies (GWh)*
Max.	29,517.67	143.81	489,643	48.00	1,116,495.39	289,966.58
Min.	9,053.28	0.00	226.00	0.00	2,765.02	3.89
Average	15,396.68	21.96	12,593.95	2.86	59,215.23	30,735.09
Stand. Dev.	4,241.77	27.54	48,337.40	5.51	123,776.14	48,112.09

Table 4.2.- Criteria values

Additionally, a minimum distance between municipalities must be applied to avoid deploying too many fueling stations in a certain area (which would be a waste of investment in the initial deployment stage). This chapter assumes that two municipalities are too close when they are less than 25 kilometres apart.

To compute this, the constraints defined in Eq. [4.5] are included with a symmetric matrix *A*, with dimension 104x104, such that

$$a_{ij} = \begin{cases} 1 & \textit{distance between municipalities } i \textit{ and } j \textit{ is lower than } 25 \textit{ km.}, \\ 0 & \textit{otherwise.} \end{cases} \qquad \text{Eq. [4.10]}$$

The application of the proposed model in this context is justified as the subgroup is considered a single entity. The evaluation of the selected subgroup seeks to go further than the sum of the individual values associated to the selected units. This justifies the use of the same set of weights and not individual evaluations as proposed in traditional DEA models. Although the weights are common to all alternatives, they are determined by the selected alternatives, in order to maximize the evaluation of the selected group.

The idea of using an endogenously-determined set of weights allows including a minimum amount of subjective information into the model. The proposed procedure evaluates each alternative exclusively by its numeric performance with regard to criteria. Several authors have pointed out that DEA based models can provide an acceptable alternative to prescriptive modelling tools for those cases in which multiple decision makers are involved, and consensus on weight values is more difficult to reach. Therefore, in situations with multiple groups of interest, as in this case, the use of decision tools which do not require a prior consensus is valuable.

The first result sought is maximum feasible size of the subgroup. Taking into account the geographical limitation referred to above, this value is equal to 21. It is determined by computing the maximum of *e* considering the geographical restrictions. Any problem which tries to determine a subset with more alternatives than this value would be characterized as infeasible.

The minisum solution for three different values of *e* (5, 10 and 20 units) is shown in Table 4.3. In all cases, the objective is maximization of the sum of evaluations of the selected alternatives. In order to ensure that all criteria are represented in the evaluation of the alternatives, a lower bound to the weighting-vector components is included, such that $w_i \geq 0.0001$, with $i = 1,\ldots, 6$. Note that in every case the selected alternatives are listed in alphabetical order.

The optimal value of *w* for the subgroup of five alternatives is the vector w^* = (0.028, 0.215, 0.0001, 0.0001, 0.0001, 0.0008). In the case of 10 and 20 alternatives, the weighting vector coincides with w^* = (0.0336, 0.0808, 0.0001, 0.0001, 0.0001, 0.0014). It is important to highlight that because of the data units, the maximum aggregate value has been established in 1,000 units (and not at the unity, as appears in the description of the model). With this modification, the values of *w* can be appreciated more clearly.

Table 4.3 shows the main alternatives selected as well as their aggregate values from the minisum solution. It is important to bear in mind that even though these values would allow ranking of alternatives, this is not the objective of the procedure. The aim is to determine the best group by optimizing the overall (summation) evaluation of the selected units.

Group of 5		Group of 10		Group of 20	
Municipality	**Value**	**Municipality**	**Value**	**Municipality**	**Value**
Carmona	1,000.00	Aznalcázar	685.99	Aznalcóllar	566.82
Écija	1,000.00	Carmona	942.76	Carmona	942.76
Osuna	758.33	Castilblanco de los Arroyos	589.79	Castilblanco de los Arroyos	589.79
Seville	1,000.00	Castillo de las Guardas (El)	568.16	Corrales (Los)	351.72
Utrera	927.03	Écija	1,000.00	Écija	1,000.00
		Lebrija	665.80	Fuentes de Andalucía	476.09
		Marchena	666.13	Guadalcanal	468.59
		Osuna	781.24	Herrera	470.32
		Seville	1,000.00	Lebrija	665.80
		Utrera	869.33	Madroño (El)	490.97
				Montellano	473.47
				Navas de la Concepción (Las)	374.75
				Pedroso (El)	503.15
				Peñaflor	468.55
				Pruna	362.33
				Puebla de Cazalla (La)	472.57
				Real de la Jara (El)	441.93
				Seville	1,000.00
				Utrera	869.33
				Villamanrique de la Condesa	507.52

Table 4.3.- Minisum solutions

Table 4.4 summarizes the minimax solution for the three cases. The optimal vector of weights is identical for the groups of 5 and 10 alternatives, w^* = (0.0336, 0.0808, 0.0001, 0.0001, 0.0001, 0.0014), and varies for the third case (20 units) to w^* = (0.0336, 0.0001, 0.0001, 0.1079, 0.0001, 0.0014). It should be noted that the solution for the case with 10 alternatives is the same as that shown in Table 4.3, since the same weighting vector was obtained.

In this latter case, the aggregate value of the worst alternative determines the solution for the group, and, therefore, results in a lower sum of the selected subgroup's evaluations (falls from 4,685.36 to 4,593.33 units in the case of a group with 5 alternatives). However, the value of the last selected alternatives increases (from 758.33 to 781.24 units in the case of the group with 5 units). The choice of the objective will depend on the preferences of the analyst or the particular context of the problem.

Group of 5		Group of 10		Group of 20	
Municipality	**Value**	**Municipality**	**Value**	**Municipality**	**Value**
Carmona	942.76	Aznalcázar	685.99	Aguadulce	417.18
Écija	1,000.00	Carmona	942.76	Alcolea del Río	403.61
Osuna	781.24	Castilblanco de los Arroyos	589.79	Algámitas	358.72
Seville	1,000.00	Castillo de las Guardas (El)	568.16	Badolatosa	363.89
Utrera	869.33	Écija	1,000.00	Cabezas de San Juan (Las)	542.28
		Lebrija	665.80	Castilblanco de los Arroyos	591.87
		Marchena	666.13	Castilleja del Campo	523.75
		Osuna	781.24	Castillo de las Guardas (El)	567.77
		Seville	1,000.00	Écija	1,000.00
		Utrera	869.33	Fuentes de Andalucía	476.61
				Guadalcanal	467.56
				Montellano	472.81
				Navas de la Concepción (Las)	374.62
				Pedroso (El)	501.69
				Peñaflor	468.62
				Puebla de Cazalla (La)	473.71
				Real de la Jara (El)	441.14
				Tomares	1,000.00
				Viso del Alcor (El)	498.87
				Isla Mayor	487.56

Table 4.4.- Minimax solutions

It is worth noting that the minimax solution for the 20 alternatives group does not select Seville, the capital of the province. The existence of alternatives with better performance in one of the two most important criteria (average income and road network), and the geographical restrictions in place, have resulted in Tomares being selected instead of Seville for the location of the station. It is possible to configure procedure to select a particular alternative by including an additional constraint. However, although this feature will ensure the selection of desired alternatives, it will be detrimental to the overall evaluation of the group and the minimax objective. The new optimal subgroup and the corresponding aggregate values are shown in Table 4.5.

Municipality	Value
Alcolea del Río	403.52
Aznalcóllar	566.82
Badolatosa	363.83
Cabezas de San Juan (Las)	543.98
Castilblanco de los Arroyos	589.79
Corrales (Los)	351.72
Écija	1,000.00
Fuentes de Andalucía	476.09
Guadalcanal	468.59
Madroño (El)	490.97
Montellano	473.47
Navas de la Concepción (Las)	374.75
Pedroso (El)	503.15
Peñaflor	468.55
Pruna	362.33
Puebla de Cazalla (La)	472.57
Real de la Jara (El)	441.93
Seville	1,000.00
Utrera	869.33
Villamanrique de la Condesa	507.52

Table 4.5.- Minimax solution II

The new optimal weighting vector is now w^* = (0.0336, 0.0808, 0.0001, 0.0001, 0.0001, 0.0014), and the selected subgroup varies considerably, with seven differences with regard to Table 4.4. The overall evaluation of the group is worse, and the minimax value has dropped from 358.72 (Algámitas) to 351.72 (Corrales (Los)). It is worth noting that, in this case, the preselected alternative influences not only the selection of the optimal vector, but also the selection of the remaining alternatives of the subgroup. There are several alternatives that no longer appear in the selected group because of their new aggregate values (lower than the ones obtained with the original vector), and there are several that no longer appear in the optimal group due to the geographical limitation (this is the case of Tomares, a municipality very close to Seville. which achieves a high aggregate value even with the new weighting vector).

4.5. Conclusions

The present chapter developed a DEA based model for selecting groups. Considering a group of alternatives to be evaluated with respect to multiple variables, inputs and outputs in DEA terminology, a procedure to select the best subgroup of units is proposed such that the global evaluation of the group is optimized. The weighting vector utilized to aggregate variables is determined as part of the procedure, according to the idea inherent in DEA models. Unlike traditional DEA models, a common weighting vector is obtained to evaluate all alternatives. The objective of the procedure itself, which includes comparison between alternatives and avoidance of level-pegging alternatives, justifies the use of a common weighting vector instead of one individual vector for each alternative.

The procedure achieves its purpose, considering a set of linear constraints and binary variables. Although all alternatives are evaluated to determine the vector of weights, only those units that are finally selected are taken into account to compute overall evaluation of the subgroup. In addition, several concepts of overall efficiency of the subgroup have been studied, in particular minisum and minimax solutions.

The inclusion of additional information has also been considered. While allowing the free selection of weights, which is a basic feature of DEA based models, the proposed procedure enables the inclusion of information on the relative importance of the variables or the eligible combinations of alternatives where such information is available. This information must be incorporated into the basic model. In any case, a linear expression of the required constraints is provided in this chapter in order to ensure linearity of the model and facilitate computation.

The proposed model has broad applications in the selection of subgroups of alternatives. Location or project portfolio selection problems are just two examples of areas of application of the proposed model. In fact, the model proposed in this chapter has been used to plan the deployment of hydrogen fueling stations in the province of Seville (Spain).

The basic model may be modified in several ways. For example, budget constraints may be included to restrict the number of units that can be selected, or additional restrictions can be added to limit the maximum number of feasible alternatives.

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CHAPTER FIVE

INCORPORATING FUELING BEHAVIOUR AND DRIVERS' PREFERENCES IN THE DESIGN OF ALTERNATIVE FUELS INFRASTRUCTURE IN A CITY

Abstract

The purpose of this chapter is to present an optimization model to plan the deployment strategy for hydrogen fueling stations in a city, when Origin-Destination (OD) data are not available. This model considers two objectives: to maximize the traffic covered by the selected hydrogen fueling stations, and minimize the average distance of the city's inhabitants to the nearest hydrogen fueling station. As OD data are assumed to be unknown, the clustering of stations in the highest traffic zones is prevented by including a specific constraining equation. This model is applied to Seville, a city in Southern Spain of about 140 km^2, with a population of around 700,000 inhabitants. This application uses the results of a survey of more than 200 Sevillian drivers on their current fueling tendencies, their fueling willingness to use alternative fuel vehicles, and their minimum requirements (regarding maximum distance to be travelled to fuel and number of stations in the city), when establishing a network of alternative fueling stations.

5.1. Introduction

So far, the transportation energy system has been mainly based on the use of fossil fuels. However, the pressing environmental problems involved in the production, transport and use of these fuels, the increasing energy demand, and the need for countries to improve energy security and reduce dependence on foreign energy sources, are leading countries to promote the use of alternative fuels in the transport sector (see, for example, [V.1]).

Some of these alternative fuels are produced domestically; some of are obtained from renewable sources. In most cases, they are less polluting than fossil fuels. In spite of these advantages, the market penetration of vehicles powered by these fuels has been slow, because their performance (in terms of speed, range, refuelling time, acceleration, etc.) was globally worse than that of fossil fuel vehicles and because their costs (vehicle and fuel costs) were usually much higher [V.2].

However, the size of this technological gap and cost differences is becoming increasingly smaller, and it is only to be expected that alternative fuel vehicles (AFVs) will soon be serious competitors of conventional vehicles. A good example of this is the Toyota FCV Mirai ([V.3]), a produced in series fuel cell vehicle, launched in 2014 by Toyota. Its performance is on a par with that of conventional fossil fuel vehicles: more than 650 km autonomy, 175 km/h maximum speed, and full tank refueling in less than 3 min. It can be leased for less than 500 USD a month, and this is within the price range of conventional sedans, and the hydrogen price per km is analogue to that of conventional fuels.

However, there are still other factors that hamper the use of AFVs. One of the most important is fuel availability ([V.4], [V.5]). Potential buyers are reluctant to buy AFVs if they feel they could face a relatively high risk of running out of fuel some distance from a fueling station ([V.6]). This is not only a matter of number of fueling stations; their geographical location is also very important, especially if the high costs associated with the deployment of alternative fuels infrastructure are to be minimized.

Both key factors in the design of an alternative fueling station network (number and location of fueling stations) should be influenced, to a greater or lesser extent, by drivers' preferences. Drivers must feel comfortable regarding the number of available fueling stations. Network design should respond to the fueling behaviour of potential early adopters in the first stages of the alternative infrastructure deployment, and converge to general drivers' fueling behaviour in the final stages.

Literature on AFV drivers' choices of fueling locations is rather limited. Most of these papers focus on plug-in electric vehicles; however, the longer fueling time required by this technology makes it difficult to extrapolate these studies to other (alternative) fuels with a fueling time similar to that of conventional vehicles ([V.7]). This chapter will consider the case of fuel cell vehicles (a fast fueling technology), although the results obtained in this chapter could be easily extrapolated to any other fast fueling technology of similar performance.

Sperling and Kitamura ([V.4] and [V.8]) carried out two surveys with revealed and stated questions in California: a larger survey of 1,528 drivers of gasoline vehicles and a smaller survey of 107 drivers of diesel vehicles, which was treated as a proxy for potential AFV drivers. They found that stated convenience to work, home and school was the primary reason for selecting a fueling station in 56% of the cases for diesel vehicle drivers, compared to the 29% for gasoline vehicle drivers. Anyway, proximity is also important for the larger sample, since in this sample they found that 71.9% of fueling locations are less than 5 minutes from their origin or destination, whereas around 60% of trips take 15 min or longer. Since in their sample most trips involving fueling originate or terminate at home or workplace, these authors state that it is not surprising that location of fueling choices tends to be close to home or the workplace. Moreover, these authors point out that a diesel network 10% the size of the gasoline network should be more than enough.

Instead, Nicholas ([V.9]) found that the volume of gasoline dispensed in an area of California was most correlated with the vehicle-kilometres travelled than with population. Kelley and Kuby ([V.7]), using a revealed preference survey of 259 drivers of compressed natural gas (CNG) vehicles at 5 CNG stations in Southern California, concluded that early infrastructure should focus on high-volume commuting routes, regardless of proximity to home locations.

All this previous research was focused mainly in the US. However, drivers fueling behaviour varies between countries since it is contingent on many factors such as country's size, population distribution, road infrastructure, cultural background and socioeconomic factors. In the Netherlands, Bunzeck et al. ([V.10]) carried out a survey of 12 revealed and stated questions to 2,970 respondents. They found that almost 75% of drivers in the survey stated that they refuel just after leaving home on the way to their destination or vice-versa, almost 20% make a round trip to refuel, and 58% of the drivers refuel their car within 5 minutes of their origin. The authors state that the survey indicates that is rather unusual for most of respondents to refuel halfway.

These different fueling behaviours can be modelled by means of different models ([V.7]). Point-based models ([V.11] - [V.14]) locate facilities considering distance to demand nodes. These types of models would be more appropriate if AFV drivers show preferences for fueling close to their origin or destination (home, workplace, etc.) instead of on their way. By contrast, flow-based models ([V.15] - [V.22]) locate facilities considering the flow within the network arcs. These models typically make use of Origin-Destination data.

They are more suitable to model cases where drivers refuel en route between origin and destination regardless of proximity to origin or destination. Hodgson and Rosing ([V.23]) integrate both approaches (proximity to home and traffic flows) into a single model, by assigning weights to each objective and assuming knowledge of the origin-destination matrix. These authors do not execute an application based on actual empirical data, but apply their model to a simulated case.

This chapter aims to contribute to the literature on the deployment of AFV infrastructure and drivers' preferences. This chapter is organised as follows. Section 5.2 presents a model to locate AFV fueling stations in a city based on the Hodgson and Rosing model, but adapted to the case where origin-destination data is not available. The case of a city is considered in this chapter because Directive 2014/94/EU on the deployment of alternative fuels infrastructure of the European Union ([V.24]) points out the importance of the deployment of an adequate AFV infrastructure in urban agglomerations in order to achieve a higher penetration market of AFVs. This chapter considers the case of fuel cell vehicles (FCVs), since, as previously mentioned, this technology is expected to become a serious competitor of conventional vehicles in the medium term. However, this model could be similarly applied to any AFV of similar characteristics.

In Section 5.3, the proposed model is applied to the case of Seville, one of the most populated cities of Spain. This application benefits from a survey aimed at obtaining information about Sevillians fueling behaviour and their preferences as to some key aspects on the design of an AFV infrastructure. Section 5.4 presents the results, which are discussed in Section 5.5. Finally, Section 5.6 contains the conclusions.

5.2. Model

The aim of this model is to locate a given number of hydrogen fueling stations (HRSs) in metropolitan areas, in order to facilitate the transition from fossil fuel vehicles to FCVs. This model will also help to identify the minimum number of HRSs required to provide a level of coverage deemed acceptable for the potential buyers of the FCVs (in comparison with the current level of coverage).

The current conventional fueling stations are taken as candidate locations for the HRSs. This is in line with some studies that state that the transition to the hydrogen economy in the transport sector will be done initially by installing hydrogen pumps at conventional stations ([V.25] - [V.28]).

This assumption takes into account the fact that the current number and location of the gas stations was the result of a long process of development and adjustment associated to the current energy system (based on the use of fossil fuels). This hypothesis considers the influence of many administrative, geographic, and socio-economic factors, that led to the current layout of the network of fueling stations in a city.

In line with this assumption, in the full maturity of the hydrogen energy system, the number and distribution of HRSs will match the current situation, since hydrogen and fossil fuel vehicles have similar performance levels. However, in the initial stages, the problem becomes one of choosing the most appropriate locations for a given number of HRSs from among the current locations of the fueling stations.

A first criterion to select the locations in the initial stages is to provide a certain level of accessibility in the entire metropolitan area ([V.23], [V.29]). This level of accessibility could be measured as the total distance from people's homes to the nearest fueling station (p-median models). This way it is implicitly assumed that FCV buyers are homogeneously distributed on a percentage basis within the metropolitan area, although some weights could be introduced in the model to give more relevance to some areas concentrating people with characteristics that define FCV buyers (if these characteristics were known). The shorter the average distance, the higher the level of accessibility. The urban area is divided into subareas, and each subarea i is characterized by the number of people p_i living in it, and its distance d_{ij} to the nearest fueling station j. This distance objective function is denoted by f_1, and the objective can be written as:

$$Min\ f_1 = Min \sum_{i=1}^{I} p_i \sum_{j=1}^{J} d_{ij} x_{ij} \qquad \text{Eq. [5.1]}$$

where x_{ij} is a binary variable taking a value of 1 if the fueling station j supplies the subarea i and 0 otherwise, I the total number of subareas, and J the total number of candidate sites.

A second criterion to locate the HRSs is to consider the vehicle kilometres travelled (VKT) within the range of each candidate site j (VKT_j). The area of influence of each fueling station is defined by a circle around each fueling station. VKT for each candidate site is then obtained by calculating how many kilometres of streets intersected each circle, and multiplying these kilometres by their annual average daily traffic (AADT). As a way to represent the fact that vehicles are more likely to refuel in a station the closer it is to them, concentric circles (and not just one) could be drawn around each fueling station to assign different weights to the VKT based on their distance to the fueling station. The purpose of this criterion is to give more importance to those candidate locations with higher VKT. This traffic intensity objective function is written as f_2, and the objective is:

$$\text{Max } f_2 = Max \sum_{j=1}^{J} \text{VKT}_j y_j \qquad \text{Eq. [5.2]}$$

where y_j is a binary variable taking a value of 1 if the fueling station (candidate site) *j* is chosen to supply hydrogen and 0 otherwise.

These two objectives can be combined in a single function by weighting each objective function with a normalized weight factor of α and 1-α. This model resembles the Hodgson and Rosing model ([V.23]). However, these authors use as f_2 a flow capturing model ([V.15]), whereas in the model proposed in this section f_2 only aims to favour candidate sites located in arcs with high traffic flows at the expense of others with low traffic flow. Flow capturing models require the availability of Origin-Destination (OD) data. These matrices are very useful to design an optimal network of HRSs ([V.17], [V.20]), helping to deal, for example, with the problem of cannibalization. However, this information is not available for all cities, and less often available for regional or national scales ([V.29]); and, although the OD matrices can be estimated, there are authors ([V.30]) that question its utility in the case of emerging technologies (such as FCVs), because the behaviour of the early-adopters of these new technologies is unknown. That is why this chapter presents a model that does not require information on OD data as input, but only data provided by traffic counters that are more widely available.

Since both objectives are dimensionally different (f_1 is measured as person-distance and f_2 as units of vehicles-distance per unit of time), the upper-lower bound normalization approach is applied to each objective function:

$$\text{Min}\left[\alpha \frac{f_1 - f_{1min}}{f_{1max} - f_{1min}} - (1-\alpha)\frac{f_2 - f_{2min}}{f_{2max} - f_{2min}}\right] \qquad \text{Eq. [5.3]}$$

where $f_{.min}$ and $f_{.max}$ are, respectively, the minimum and maximum attainable values in each objective function. This bi-objective model can be used to analyse the trade-off between the two objective functions.

This optimization is subject to some constraints. Eq. [5.4] requires the demand of each subarea *i* to be assigned to one and only one HRS *j*.

$$\sum_{j=1}^{J} x_{ij} = 1 \qquad \forall i \qquad \text{Eq. [5.4]}$$

Eq. [5.5] allows demand of a subarea *i* to be assigned to a candidate site *j* only if an HRS is sited there.

$$x_{ij} \leq y_j \quad \forall i,j \qquad \text{Eq. [5.5]}$$

Eq. [5.6] sets the total number of HRSs to be sited (denoted by *P*):

$$\sum_{j=1}^{J} y_j = P \qquad \text{Eq. [5.6]}$$

Finally, Eq. [5.7] deals with the fact that we could have several candidate sites that potentially serve overlapping demand. Eq. [5.7] is written as:

$$\sum_{j \in P_k} y_j \leq \frac{P}{J} \left(|P_k| - 1 \right) + 1 \quad \forall k \qquad \text{Eq. [5.7]}$$

where P_k denotes the set of other candidate sites that potentially serve overlapping demand with candidate site *k,* and $|P_k|$ the cardinality of that set.

To explain this constraint, let's consider as an example the case where some candidate sites are located on the same arc *k*. In this case, if this arc has the highest flow and *P* is lower than the number of candidate sites on that arc $|P_k|$, all the HRSs would be placed in that arc, ignoring the fact that they are all intercepting (or partially intercepting) the same flow. Eq. [5.7] sets an upper bound on the number of HRSs that can be placed in that arc (in other words, this constraint prevents cannibalization by stations with overlapping demand), with this bound being related to the number of candidate sites, the number of HRSs to be located, and the current number of fueling stations in that arc *k*.

This constraint takes the current distribution of fueling stations into account to set an upper bound on the number of fueling stations that can be placed in that arc *k* as a function of *P* and $|P_k|$. In this way, information from the current fueling station distribution on the number of fueling stations in that arc, compatible with cannibalization, is incorporated into the model.

Note that, when the value of *P* is low (initial stage of the transition to FCVs), this constraint will lead to the selecting of only one station in that arc. However, when the value of *P* is higher (a high demand of hydrogen for vehicles), the location of more than one HRS in that arc will be allowed since the risk of cannibalization will be lower. This is due to the fact that the current distribution of the fueling stations provides information on the number of fueling stations that can be located in that arc *k* in spite of cannibalization. Similarly, if the value of $|P_k|$ and the traffic flow in arc *k* is high, the location of more than one HRS in that arc will be allowed. This will be the case, for example, of a city with only one main avenue.

Figure 5.1 shows the maximum number of HRSs allowed for different values of *P/J* when $|P_k|$ HRSs have overlapping demand. Obviously, other types of functions for the maximum number of HRSs allowed, when overlapping demand exists, could have been considered in Eq. [5.7].

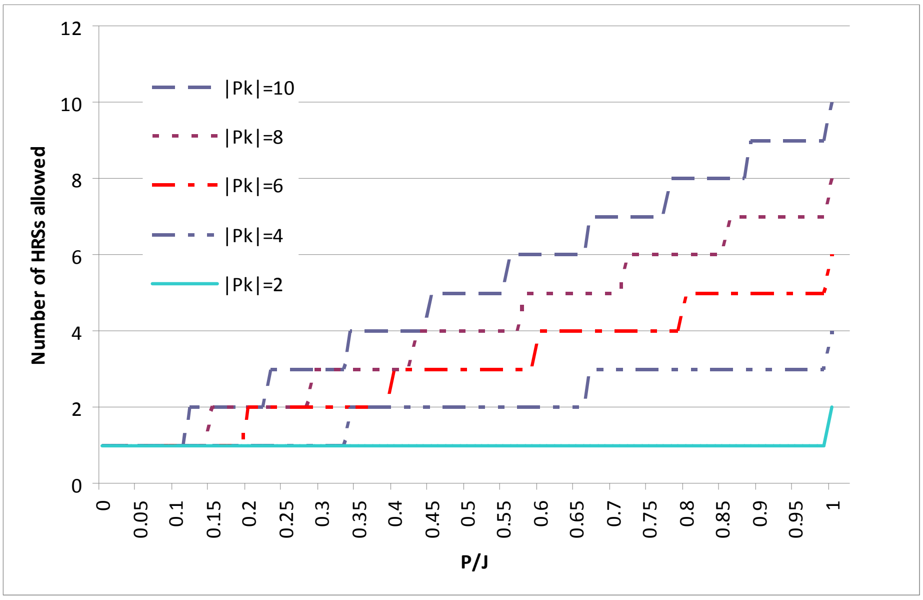

Figure 5.1.- Maximum number of HRSs allowed for $|P_k|$ stations with overlapping demand by Eq. [5.7] for different values of *P/J*

5.3. Practical application

The model developed in the previous Section will be applied in the case of the city of Seville. Seville is the capital of Andalusia, the largest region in Spain, located in the South of this country. Seville is the fourth most populous Spanish city, with a population of around 700,000 inhabitants, and an area of approximately 140 km^2. The importance of this city makes it a candidate for consideration as a major urban agglomeration with a view to locating hydrogen fueling stations in compliance with the Directive 2014/94/EU on the deployment of alternative fuels infrastructure ([V.24]), if adopted by Andalusia or Spain.

In order to compute f_1 (see Eq. [5.1]), Seville was divided into subareas by using the 517 census units of Seville available in 2012, and the population of each census unit was established ([V.31]) (See Figure 5.2). Next, the distances from the unit census (or, to be more precise, their centroids) to the fueling stations that existed in Seville in 2012 were computed. As previously mentioned, these stations were taken as potential candidate sites.

In order to compute f_2 (see Eq. [5.2]), the VKT for each candidate site was computed by defining concentric circles with a radius of 500 m and 1,000 m around each fueling station, and following the procedure detailed in Section 5.2. The VKT in the inner circle were given a weight of 1, whereas the VKT in the area between the outer and the inner circle were given a weight of 0.5. Data on the annual average daily traffic (AADT) in Seville for 2012 were obtained from [V.32] (See Figure 5.3).

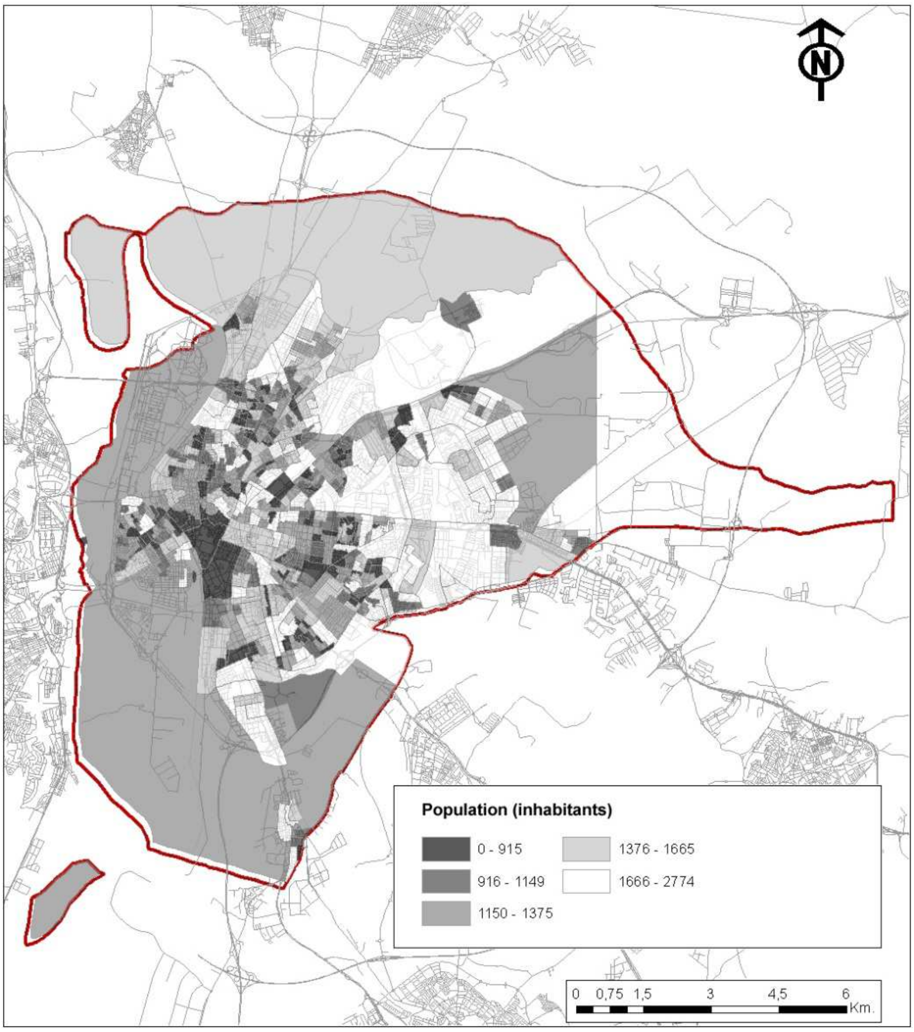

Figure 5.2.- Population of each census unit of Seville

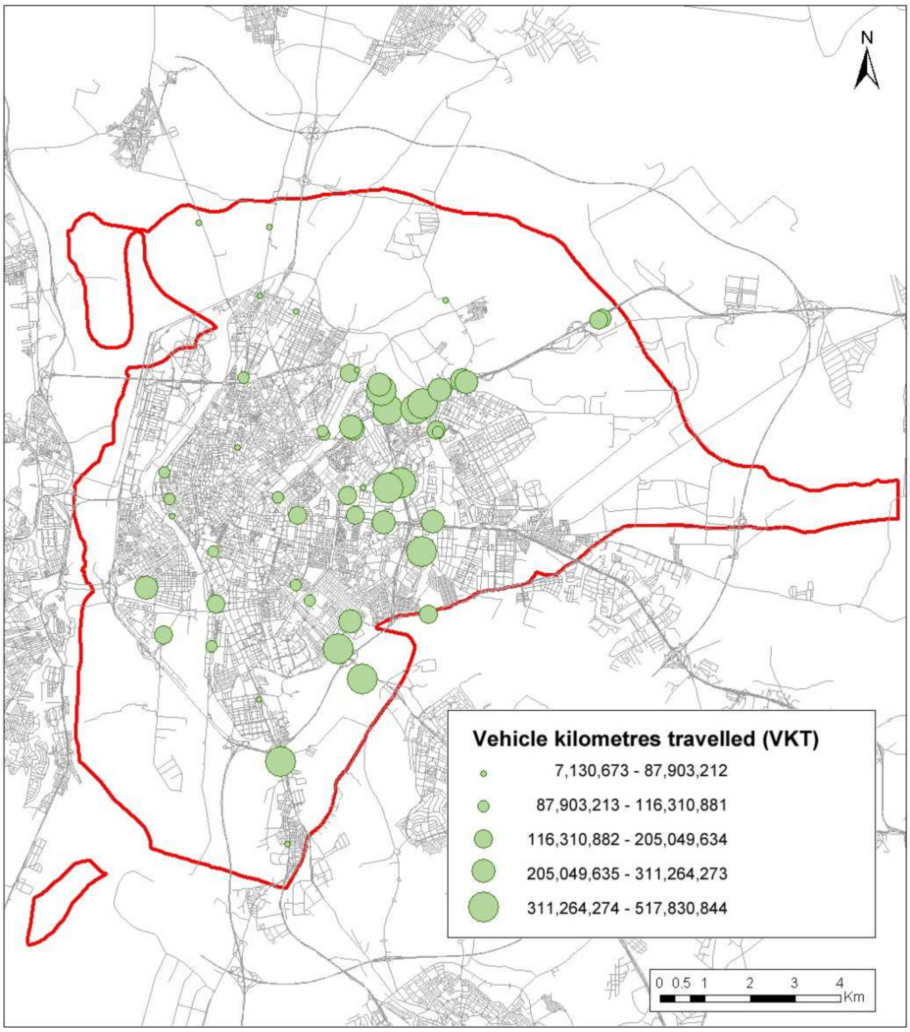

Figure 5.3.- Vehicle kilometres travelled within the range of each candidate site *j* (VKT_j)

5.3.1. Eliciting Sevillian drivers' preferences: A survey

The application of the model requires information on the drivers' fueling behaviour and their demands as regards the hydrogen fueling infrastructure. To obtain this information, a survey was carried in Seville in the first quarter of 2015. A stratified random sample of 230 Sevillian drivers that make fueling decisions was surveyed by phone. The strata were gender and age, and they were defined according to the statistics on Spanish drivers ([V.33], [V.34]).

The questionnaire was short, including only 12 questions, 5 of which were socio-demographic. The first question (Q1) was a revealed preference question addressed to identify the main factors driving the driver's choice of fueling location. The purpose was to gain knowledge on the value of α (see Eq. [5.3]). Several pre-tests were needed to formulate these questions, as many factors with different weights and/or relations of predominance and subordination may affect the choice of fueling location. That is why multiple choices were allowed in Q1, including the "Other, please specify" open-ended response, and some follow-up questions were included for some choices. The responses to this question allowed us to classify respondents into drivers fueling in a fueling station close to their home or usual destination, on their way to a destination, doing a specific round trip to refuel, or combination of the previous categories. Table 5.1 shows the final grouping obtained from the responses to Q1.

	Frequency	Percentage
Proximity	109	47.39%
Proximity and fueling station characteristics	21	9.13%
On the way	7	3.04%
On the way and fueling station characteristics	58	25.22%
Fueling station characteristics (Round trip)	33	14.35%
Missing values	2	0.87%

Table 5.1.- Main factors driving drivers' choice of fueling location

Table 5.1 shows that nobody chose the factors "Proximity" and "On the way" together although, as mentioned earlier, this combination was allowed. It is also worth noting that the particular characteristics of the fueling stations (such as price, fuel quality or the existence of full-service) are highly considered by some drivers when choosing where to refuel. In fact, 14.35% of the sample stated that they make specific round trips to refuel in a particular fueling station due to its characteristics. However, this factor is not related to the deployment of the fueling stations but to the station itself.

After removal of the 2 missing values, the categories showed in Table 5.1 can be grouped into three categories: those that refuel close to origin or destination (57.02%), those that fuel on the way (28.51%), and those that make a specific round trip to refuel (14.47%). The drivers included in the first group (proximity) can be subsequently grouped according to their responses into proximity to home (74.65%) and proximity to usual destination (25.35%).

As a conclusion, the responses to Q1 show that, in planning the deployment of AFV infrastructure for the case of Seville, proximity to home is to be weighted more heavily than traffic intensity (on the way fueling); to be precise, the estimated value for α is 130/195, that is, $\alpha=0.67$.

The second block of the survey was composed of five stated preference questions concerning the use of alternative fuels and the AFV infrastructure. The first and second questions of this block (Q2 and Q3) were addressed to identify those individuals reluctant to buy AFVs. Individuals were asked if they would be willing to buy an AFV with the same performance of conventional diesel and gasoline vehicles, but non-polluting (Q2). Therefore, AFVs were assumed to be a dominant alternative with respect to conventional vehicles. In spite of that, 19 respondents of the sample rejected the idea of buying an AFV or did not answer this question. These individuals were removed for the analysis of the next responses. These individuals justified their responses in most of the cases (Q3) by explaining that they are not confident about the use of alternative fuels and are satisfied with the conventional vehicles performance.

The last four questions (Q4 - Q7) of this second block focused on the factors “Proximity of the alternative fueling station (ARS) to home” and “Number of alternative fueling stations (ARSs) in the city”. For each factor, each driver was required to rate its importance on a 7-point Likert scale (Q4 and Q6) ranging from 1 (not important at all) to 7 (very important), and to state their maximum and minimum required value of these factors respectively to consider buying an AFV (Q5 and Q7).

Columns 4-7 in Table 5.2 show some measures of central tendency and spread for these 4 variables. Columns 8 and 9 report the p-values of the z-scores for skewness and the Shapiro-Wilk normality tests, respectively. The data sets showed skewed responses (at a significance level of 1%) with some potential outliers. In these cases, the median and the interquantile range (IQR) are often used as measures of central tendency and spread, respectively, as they are robust against outliers and non-normal data, thereby avoiding having to make decisions about the identification and treatment of outliers ([V.35], [V.36]). For these reasons, medians will be used in the next sections as a measure of the central tendency of these data.

		Number of responses	Mean	Median	Standard deviation	IQR	z-score for skewness (p-value)
Proximity of the ARS to home	Importance (1-7 scale) (Q4)	211	6.379	7.000	1.195	1.000	0.000
	Maximum value required (minutes) (Q5)	209	9.699	10.000	5.066	5.000	0.000
Number of ARSs in the city	Importance (1-7 scale) (Q6)	211	6.275	7.000	1.401	1.000	0.000
	Minimum value required (Q7)	173	21.353	10.000	45.329	17.500	0.000

Table 5.2.- Summary statistics of questions Q4, Q5, Q6, and Q7

Responses to questions Q4 and Q6 show not statistically significant differences between the importance of the two factors considered (Q4 and Q6). Sevillian drivers consider the location of an ARS close to their home to be as important as the number of ARSs in the city, with both factors being extremely important for drivers.

Finally, the third block contains 5 socio-demographic questions.

5.3.2. Calculation

The model was optimized for different values of P and α. The range of values of P goes from 2 (the minimum value of HRSs to guarantee fuel availability in the city with a back-up station) to 10 (the central value provided by drivers in the survey. See Table 5.2). The in between values considered were 4, 6, 7 and 8. Regarding α, 9 scenarios were considered, ranging from 0 (more importance to traffic intensity) to 1 (more importance to proximity to home): 0, 0.1, 0.25, 0.33, 0.5, 0.67, 0.75, 0.9, and 1.

The optimization problem was solved generating all the combinations and taking the one minimizing the objective function.

For this application, P_k (see Eq. [5.7]) was defined by following the homogeneous traffic zones defined by [V.32].

5.4. Results and discussion

Information on refueling behaviour and preferences of potential consumers is a key input to design an efficient network of HRSs. This information is very contingent on the area where the hydrogen fueling infrastructure is going to be deployed. The survey conducted in Seville has shown that proximity to home is the main factor affecting current Sevillian drivers' refueling behaviour. Sevillian drivers are more prone to refuel close to their home than en route to a destination.

Moreover, Sevillian drivers stated that the number of HRSs in the city and their proximity to their homes are two factors that they consider very highly in their decisions to change over to FCVs or any other AFV. The median value of the required proximity is 10 minutes driving distance. Regarding the number of ARSs, respondents report a median value of 10, and find it quite difficult to provide a value (see response rate to Q7 in Table 5.2).

All this information is not only very useful to develop the model described in Section 5.3, but also to restrict the relevant parametric space for some parameters included in said model (that is, the values of P and α).

Table 5.3 shows the results obtained for different relevant values of *P* and α. As expected, the higher the value of *P*, the lower the average distance (f_1) and the higher the VKT (f_2). Moreover, there is a trade-off between both objectives for the different values of α when *P* is kept constant. This behaviour can also be seen in Figure 5.4. This Figure shows the different Pareto-optimal curves for different values of *P*. Each curve has been plotted using the points obtained for the aforementioned values of α.

Information obtained from the survey is used now to recommend specific points within the set of non-dominated solutions. The dashed line in Figure 5.4 shows the set of non-dominated points for α=0.67, the value of α estimated from the survey. This line is a concave-up decreasing curve, where changes in the value of f_1* when *P* increases, are smaller on the left-hand side of the curve than on the right hand-side of the curve.

P	α	f_1*	f_2	Fueling stations selected**
2	0.00	3,336.948	928,266.918	12, 51
2	0.10	2,840.236	901,680.721	39, 51
2	0.25	2,840.236	901,680.721	39, 51
2	0.33	2,840.236	901,680.721	39, 51
2	0.50	2,407.785	626,180.589	13, 51
2	0.67	2,280.648	355,244.528	32, 46
2	0.75	2,280.648	355,244.528	32, 46
2	0.90	2,280.648	355,244.528	32, 46
2	1.00	2,274.107	217,057.798	21, 25
4	0.00	2,867.824	1,737,505.802	12, 41, 42, 51
4	0.10	2,653.324	1,720,027.326	12, 39, 42, 51
4	0.25	2,140.577	1,580,518.025	12, 38, 39, 51

4	0.33	2,124.289	1,571,902.969	38, 39, 50, 51
4	0.50	1,861.774	1,356,097.156	12, 32, 39, 51
4	0.67	1,699.770	1,106,667.542	12, 32, 38, 39
4	0.75	1,625.149	833,029.849	2, 12, 32, 38
4	0.90	1,549.845	358,406.578	2, 6, 32, 48
4	1.00	1,549.845	358,406.578	2, 6, 32, 48
6	0.00	2,704.082	2,364,692.649	12, 18, 19, 33, 41, 51
6	0.10	2,097.602	2,306,678.154	12, 19, 33, 38, 41, 51
6	0.25	1,986.969	2,280,584.621	19, 33, 38, 39, 50, 51
6	0.33	1643.936	2,073,748.083	12, 13, 33, 38, 39, 51
6	0.50	1,568.718	2,009,378.587	12, 32, 33, 38, 39, 51
6	0.67	1,420.789	1,650,623.742	19, 25, 32, 33, 38, 51
6	0.75	1,420.789	1,650,623.742	19, 25, 32, 33, 38, 51
6	0.90	1,303.866	910,139.477	2, 6, 13, 33, 37, 48
6	1.00	1,296.799	605,841.446	2, 6, 13, 26, 37, 48
7	0.00	2,565.057	2,675,956.872	12, 18, 19, 33, 41, 46, 51
7	0.10	2,055.333	2,633,093.823	12, 18, 19, 33, 38, 41, 51
7	0.25	1,944.700	2,607,000.291	18, 19, 33, 38, 39, 50, 51
7	0.33	1,576.494	2,397,549.479	12, 13, 19, 33, 38, 39, 51
7	0.50	1,500.756	2,333,179.982	12, 19, 32, 33, 38, 39, 51
7	0.67	1,387.702	2,089,596.494	13, 19, 33, 37, 38, 39, 51
7	0.75	1,354.061	1,979,676.181	13, 19, 33, 37, 38, 39, 42
7	0.90	1,217.401	1,233,940.873	2, 6, 13, 19, 33, 37, 48
7	1.00	1,208.889	931,160.426	6, 13, 19, 25, 26, 37, 48
8	0.00	2,530.301	3,083,867.347	12, 18, 19, 33, 41, 42, 46, 51
8	0.10	2,020.577	3,041,004.298	12, 18, 19, 33, 38, 41, 42, 51
8	0.25	1,904.758	3,014,910.766	18, 19, 33, 38, 39, 42, 50, 51
8	0.33	1,541.022	2,805,459.954	12, 13, 19, 33, 38, 39, 42, 51
8	0.50	1,454.842	2,732,475.400	19, 32, 33, 38, 39, 42, 50, 51
8	0.67	1,344.519	2,497,506.969	13, 19, 33, 37, 38, 39, 42, 51
8	0.75	1,344.519	2,497,506.969	13, 19, 33, 37, 38, 39, 42, 51
8	0.90	1,154.124	1,286,467.703	2, 6, 19, 32, 33, 37, 44, 48
8	1.00	1,146.467	915,160.527	2, 6, 19, 26, 29, 32, 44, 48
10	0.00	1,920.475	3,658,915.031	11, 12, 18, 19, 33, 38, 41, 42, 46, 51
10	0.10	1,920.475	3,658,915.031	11, 12, 18, 19, 33, 38, 41, 42, 46, 51
10	0.25	1,725.759	3,590,292.304	12, 18, 19, 33, 35, 38, 39, 42, 46, 51
10	0.33	1,477.186	3,443,139.846	12, 13, 18, 19, 33, 38, 39, 42, 46, 51
10	0.50	1,397.918	3,378,770.350	12, 18, 19, 32, 33, 38, 39, 42, 46, 51
10	0.67	1,290.315	3,202,052.437	11, 12, 13, 33, 37, 38, 39, 42, 46, 51
10	0.75	1,240.366	3,011,057.866	13, 19, 25, 33, 37, 38, 39, 42, 50, 51
10	0.90	1,134.978	2,535,910.293	11, 13, 16, 25, 33, 37, 39, 46, 48, 51
10	1.00	1,048.349	1,054,210.610	2, 6, 8, 19, 21, 26, 29, 32, 44, 48

*Average distance (in meters)
**See Figure 5.6

Table 5.3.- Fueling stations selected as a function of P and α

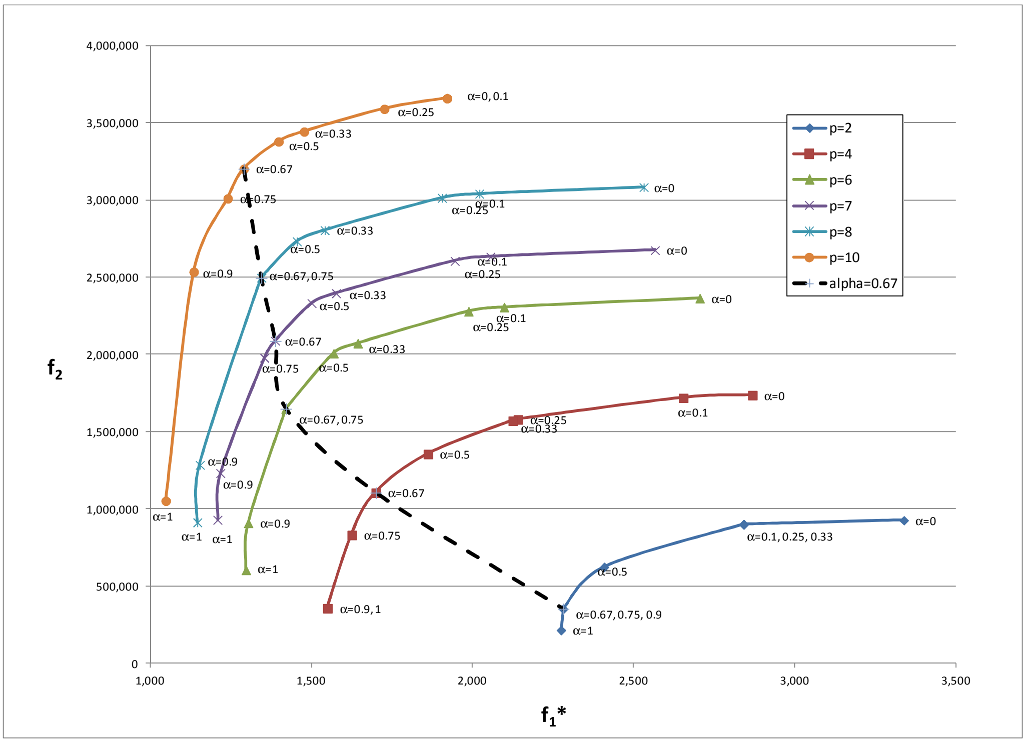

Figure 5.4.- Pareto-optimal curves for different values of *P*. Symbols are from the optimization model, while the connecting lines are just guides for the eye

Information on the value of *P* was also provided by the survey. A central value of *P*=10 was obtained (see Table 5.2). This way, only one point from the set of non-dominated points is finally recommended.

The survey also provided information on the maximum distance from home to the nearest station (driving distance in minutes) required by the respondents (Q5). The value of the median (and mean) of the Q5 responses is around 10 minutes. For the selected point (*P*=10 and α=0.67), that distance is 1,290.315 m. The minimum average speed required in a city to cover that distance in 10 minutes is around 8 km/h, which is lower than the average speed of 21.78 km/h estimated for Seville by the Seville Traffic Management Centre[7]. Therefore, the solution recommended also satisfies the distance constraint stated by the respondents. Otherwise, the minimum value of *P* (being *P*>10) verifying the distance constraint (given an average speed in the city) with α=0.67 should have been selected (see Figure 5.5).

[7] Information obtained from personal interview with staff of the Seville Traffic Management Centre.

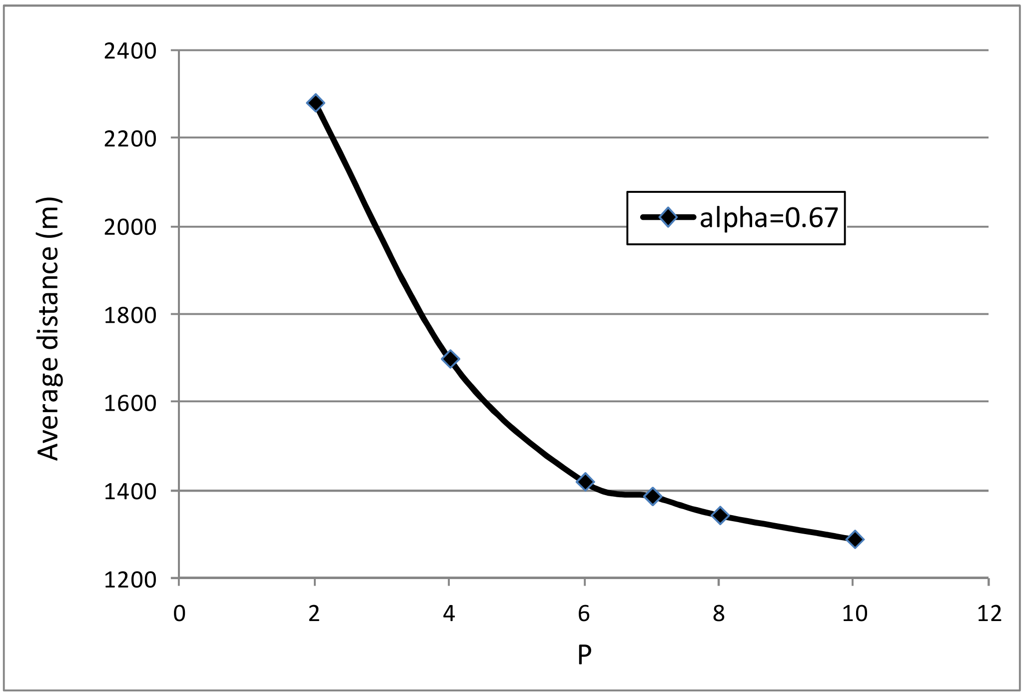

Figure 5.5.- Average distance (in meters) as a function of *P*. Symbols are from the optimization model, while the connecting lines are just guides for the eye

Figure 5.6 shows the location of the fueling stations selected for the case of *P*=10 and α=0.67.

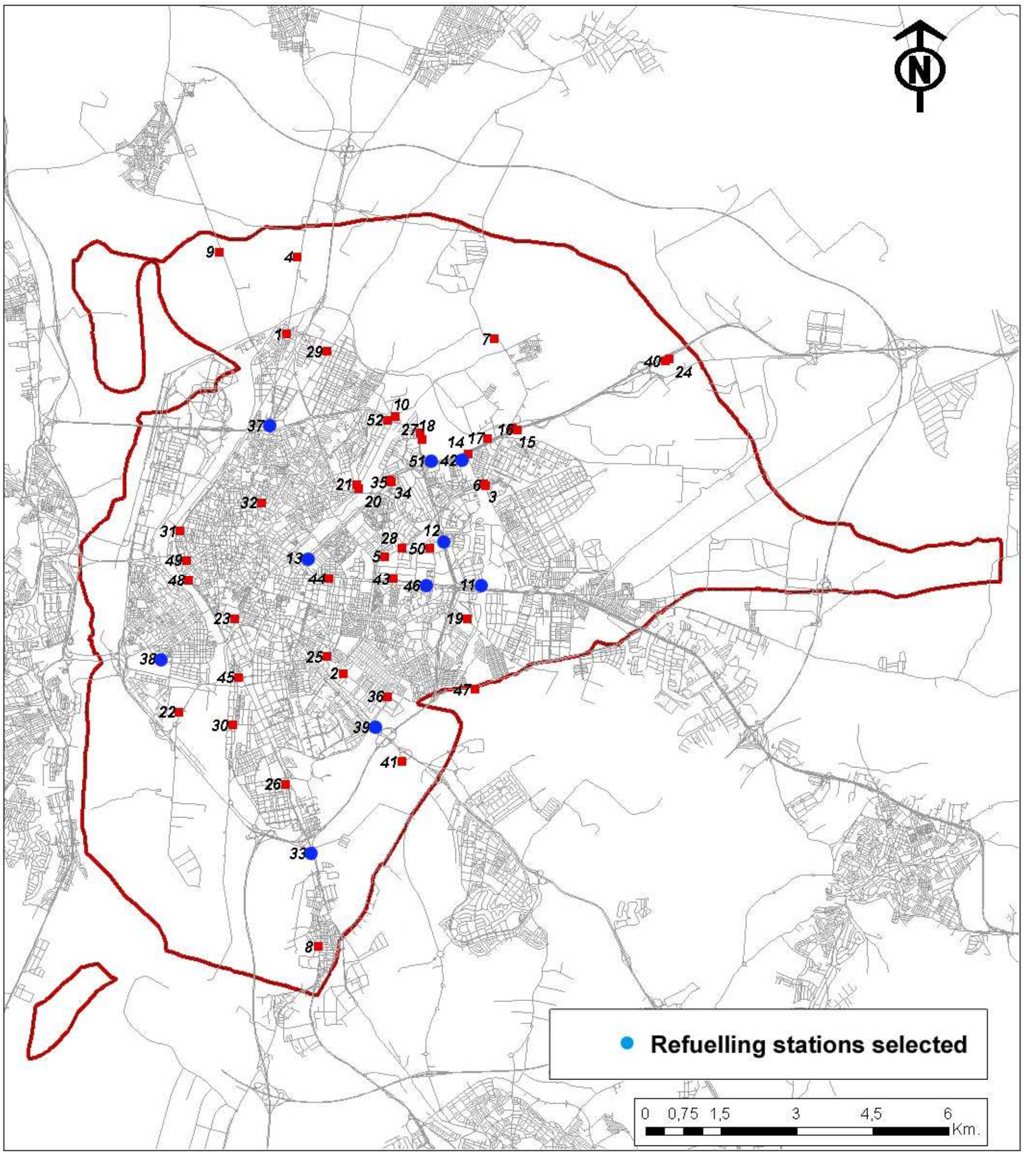

Figure 5.6.- Fueling stations selected (P=10 and α=0.67)

5.5. Conclusions

The purpose of this chapter is to present an optimization model to plan the deployment strategy for HRSs in a city when Origin-Destination data are not available. This model considers two weighted objectives: maximize the traffic covered by the selected fueling stations and minimize the average distance of the city's inhabitants to the nearest HRS.

As OD data are assumed to be unknown, the proposed model prevents the clustering of stations in the highest traffic zones by including a specific constraining equation. This constraint limits the number of HRSs to be located in a zone, as a function of the total number of stations to be installed in the city and the number of current conventional fueling stations in the zones.

This model is applied to the city of Seville. This application benefits from the results of a survey of more than 200 Sevillian drivers on their current fueling behaviour and their preferences regarding the design of a network of alternative fueling stations in terms of maximum required distance from home to refuel and number of stations in the city.

The results of the survey show that Sevillian drivers give great importance to the existence of fueling stations close to their home. Moreover, in order to buy AFVs, they typically want to have the closest ARS not more than 10 minutes (driving distance) away and an alternative fuels infrastructure in the city with at least 10 fueling stations. These survey results allowed recommendation of one particular point of the set of non-dominated solutions to the model (P=10 and α=0.67).

Of course, the results from the survey are particular to the case of Seville but can be estimated similarly for other cities, allowing the model to better capture the fueling tendencies and preferences of each city. It is also worth noting that the model captures most of the different fueling behaviour that can be affected by the network design.

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CONCLUSIONES

En esta Tesis Doctoral, se han desarrollado y analizado diversos métodos que pueden ser empleados para planificar, de forma eficiente, el despliegue de infraestructura de forma que se facilite la adopción del hidrógeno como combustible en el sector transporte. Además, dichos métodos han sido aplicados a diferentes ámbitos territoriales (país, región, provincia y ciudad), poniendo así de manifiesto las peculiaridades que pueden existir en función del nivel territorial de análisis.

Son diversas y variadas las conclusiones que pueden extraerse de la lectura de los cinco capítulos que conforman la presente Tesis. A continuación, se recogen algunas de ellas:

- Aunque muchas veces resulte un tópico, el problema del huevo y la gallina existe. Los potenciales usuarios siguen viendo los combustibles alternativos y, entre ellos, el hidrógeno, como algo poco confiable, siendo la falta de infraestructura uno de los principales escollos a la hora de adquirir un vehículo que emplee este combustible.
- La planificación óptima del despliegue de infraestructuras es fundamental para lograr una transición exitosa hacia modelos energéticos alternativos en el sector transporte. Dado el alto coste de este tipo de despliegues, es evidente que esta planificación ha de realizarse de la forma más eficiente posible, llegando al mayor número de potenciales usuarios con la mínima inversión.
- La identificación de estos primeros usuarios (“early adopters”) de tecnología es especialmente relevante en las fases iniciales del despliegue. Siempre existirán zonas más proclives a la adopción de estas nuevas tecnologías; no es recomendable suponer que los consumidores (la demanda) estarán homogéneamente distribuidos. Por ello, el desarrollo preferente de unas ciertas zonas al inicio de la estrategia de despliegue se perfila como una estrategia más eficiente que el intento de una cobertura geográfica total. Los resultados obtenidos en la presente Tesis Doctoral han permitido identificar dichas zonas para el caso de la España peninsular y la Comunidad Autónoma de Andalucía. En el caso de la España peninsular, y para una fase inicial del despliegue, esas zonas corresponden al norte de España, el centro de la Península Ibérica y la costa mediterránea. En el caso de la Comunidad Autónoma Andaluza, y para una fase más avanzada, donde ya adquiera una mayor importancia la producción del hidrógeno mediante fuentes renovables, las zonas preferentes se localizan en la parte occidental de la región.

- Una forma de identificar las zonas idóneas para el establecimiento de estaciones de servicio de suministro de combustibles alternativos, atendiendo a múltiples criterios, es agregar los valores normalizados de las zonas para los diferentes criterios mediante una serie de ponderaciones. Como se ha mostrado en esta Tesis Doctoral, estos pesos pueden ser obtenidos a partir de expertos en la materia, o mediante algún modelo que proporcione de manera endógena dichos pesos en base a algún criterio. La experiencia obtenida en este trabajo ha mostrado que la primera de las opciones (un buen sistema de pesos y normalizaciones consensuados con expertos en la materia) tiende a proporcionar mejores resultados.
- La planificación no ha de basarse solamente en la identificación de los potenciales usuarios, sino que también han de tener en cuenta sus preferencias en cuanto al repostaje y otros aspectos de la red de suministro. Los individuos siguen unos determinados criterios a la hora de escoger la estación de servicio a la que van a repostar habitualmente. Entre esos criterios, la localización de la estación de servicio juega un papel muy relevante (por ejemplo, cerca del domicilio, del lugar de trabajo, en el camino hacia algún destino concreto, etc.). Este tipo de información ha de tenerse en cuenta a la hora de diseñar una red de estaciones de servicio de suministro de combustibles alternativos, puesto que la probabilidad de que los individuos adopten estos combustibles será mayor en la medida en la que la red responda a sus necesidades. De forma similar, hay que tener en cuenta las preferencias de los potenciales usuarios respecto a otros aspectos del diseño de la red, como pudiera ser el número mínimo de estaciones de servicio y/o la máxima distancia a la estación más cercana que estarían dispuestos a aceptar para adquirir un vehículo con combustible alternativo. Así, por ejemplo, diseñar una red en una ciudad con un número de estaciones demasiado pequeño puede llevar al fracaso del proceso de transición en dicha ciudad, al considerar los potenciales usuarios que el combustible alternativo no está lo suficientemente disponible.
- En relación también con el punto anterior de la importancia de las preferencias de los individuos, la red ha de transmitir a los consumidores una cierta sensación de seguridad, que se refleja en distancias reducidas entre estaciones de servicio interurbanas, o en la redundancia en el caso de intraurbanas.
- Dada la importancia de las preferencias de los conductores en el diseño de la red, las encuestas se perfilan como una herramienta útil para lograr un diseño óptimo de la misma.

- El diseño óptimo es contingente del entorno en el que se realiza y de la fase del proceso de despliegue. Conocer las características del emplazamiento, así como las preferencias de los usuarios, es imprescindible. Por un lado, la idoneidad de una zona para el establecimiento de estaciones de servicio de hidrógeno no es un concepto estático, sino dinámico que varía según la fase del proceso de despliegue. Por otro, como se ha mencionado anteriormente, el diseño óptimo ha de atender a las preferencias de los individuos, las cuales pueden variar de una zona a otra.
- Particularmente, en el caso de Sevilla, la encuesta realizada en esta Tesis Doctoral ha mostrado la existencia de diferencias en el comportamiento en cuanto al repostaje de los conductores sevillanos con respecto, por ejemplo, a los casos que se analizan en la literatura sobre Estados Unidos y ciudades californianas. Gran parte de los conductores sevillanos prefiere repostar en gasolineras cercanas a sus hogares, más que durante su desplazamiento a algún destino habitual.
- Es posible definir modelos que recojan, en cada caso, las particularidades del despliegue a realizar. Estos modelos podrían ser empleados en diferentes circunstancias, no siendo necesario recurrir a métodos ad hoc en cada caso.
- El diseño de la infraestructura de estaciones de servicio en las ciudades (intraurbano) requiere de aproximaciones y herramientas diferentes de los casos regionales (interurbanos) o nacionales. Pueden distinguirse por tanto dos niveles diferentes de análisis territorial. En un primer nivel (nacional o regional) el mayor énfasis se pone en identificar los principales focos atendiendo a diversos criterios, para posteriormente localizar las estaciones de servicio en las grandes redes viarias que los unen, situándolas con una cierta distancia máxima de separación, de forma que proporcionen a los conductores una cierta seguridad en el suministro. En un nivel más detallado (ciudad), el objetivo es localizar de una forma más concreta las estaciones dentro de la ciudad, atendiendo al comportamiento y a las preferencias de los conductores.
- Los costes de una infraestructura bien desplegada, que permita acceder al máximo de la demanda con la mínima inversión, no son tan elevados. Una estrategia bien diseñada puede permitir satisfacer una demanda inicial con un pequeño porcentaje de la infraestructura con la que, actualmente, cuentan los combustibles convencionales. En el caso de Andalucía, por ejemplo, una inversión de unos 700 millones de euros sería suficiente para abastecer una flota de alrededor de 400.000 vehículos; en el caso de Sevilla, tan solo 10 estaciones de servicio de

hidrógeno serían suficientes para iniciar un proceso de transición con un nivel de aceptación adecuado por parte de los usuarios.

- Este trabajo ha puesto también de manifiesto la necesidad de abordar el tema de la planificación de infraestructura de repostaje de combustibles alternativos desde una perspectiva multidisciplinar, integrando diferentes campos científicos tales como Economía, Geografía, Ingeniería o Matemáticas.

Finalmente, cabe señalar que aunque esta Tesis Doctoral se ha centrado en el empleo del hidrógeno como combustible, los procedimientos propuestos y los resultados obtenidos pueden ser fácilmente extrapolados a otros combustibles basados en energías renovables, siempre que proporcionen un tiempo de repostaje similar a los combustibles convencionales.