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Deployment of a hydrogen supply chain by multi-objective/multi-period optimisation at regional and national scales

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ABSTRACT

This study focuses on the development of a methodological framework for the design of a five-echelon hydrogen supply chain (HSC) (energy source, production, storage, transportation and fuelling station) considering the geographic level of implementation. The formulation based on mixed integer linear programming involves a multi-criteria approach where three objectives have to be optimised simultaneously, i.e., cost, global warming potential and safety risk. The objective is twofold: first, to test the robustness of the method proposed in De-Leon (2014) from a regional to a national geographic scale and, secondly, to examine the consistency of the results. A new phase of data collection and demand scenarios are performed to be adapted to the French case based on the analysis of roadmaps. In this case study, the ArcGIS® spatial tool is used to locate the supply chain elements before and after optimisation. The multi-objective optimisation approach by the ε-constraint method is applied, analysed and discussed. Finally, a comparison between the results of different geographic scale cases is carried out.

1. Introduction

Hydrogen produced from renewable sources and used in fuel cells both for mobile and stationary applications constitutes a very promising energy carrier in a context of sustainable development. A key point in the development of the hydrogen supply chain is the demonstration of feasibility of its infrastructure while many technical, economic and social obstacles must be overcome. Some strategic roadmaps were currently reported about the energy potentialities of hydrogen at European, national and regional levels. Their main objective is to evaluate some industrial, technological, environmental and social issues and to identify the main obstacles associated to the hydrogen economy. The literature review of recent dedicated scientific publications emphasises the need for the development of systemic studies in order to demonstrate the feasibility of the sector, to validate the technical and economic interest in the production and recovery of hydrogen produced from renewable sources. Such works involve the development of models based on economic scenarios for hydrogen deployment. In that context, this work only focuses on the study of hydrogen supply chain (HSC) for transport application, more precisely, the use of H_2 in fuel cell electric vehicles (FCEVs).

The HSC can be tackled with different levels (i.e. strategic, tactical and operational). This work focuses on the strategic approach that can take place considering different geographic scales according to the defined problem. Even if in some countries, a region or a state has noticeably taken a key role as a pilot state concerning the hydrogen economy, the future of the HSC obviously depends on the interconnection among

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big cities and countries. Intercontinental analysis seems now premature but a national study can be analysed with real constraints and data.

The H_2 Mobility roadmap (Williamson, 2010) reported that Germany and Great Britain have already introduced pilot projects for the use of FCEVs while study initiatives started in France in 2013. In this country, a regional case study for the Midi-Pyrénées region was recently conducted (De-Leon, 2014). One of the main questions arising from the Midi-Pyrénées case is whether or not the geographic segmentation that was adopted (i.e. regional scale) could be changed to ensure a more competitive cost without affecting environmental and safety criteria. A new geographic scale is thus considered in this paper in order to study the feasibility of large-scale hydrogen production in France.

France is the largest country in Western Europe and the third-largest in Europe as a whole with a total population of around 65.5 million (Insee, 2013). Transportation is a major contributor to greenhouse gas (GHG) emissions in France. In 2009, the final energy consumption due to transportation was 49.8 Mtoe and the associated GHG emissions resulted in 132 Mt CO_2-equiv. In general terms, the total emissions in France decreased (mainly due to electricity mix based on very low carbon emission technologies as nuclear and hydropower) between 1990 and 2009 but those associated to the transport sector increased in the same period (Direction, 2013). The French government adopted a Climate Plan in 2004 which requires a 75% reduction in GHG emissions by 2050 compared to current levels.

If the FCEV is able to gain an important market share, hydrogen availability must be guaranteed at an intercontinental supply chain. France has a strategic location because Spain, Andorra, Italy, Switzerland, Germany, Luxemburg and Belgium are all neighbouring countries. Besides, French hydrogen production was of 7 billion N m^3 in 2007 and there are 10 production plants already installed throughout the territory (Phyrenees, 2009). The most of hydrogen is produced onsite for captive uses for the chemical industry by steam methane reforming (SMR).

The remainder of this paper is organised as follows: Section 2 is devoted to a brief literature review to highlight the objectives of this work. The methodology aspects and formulation of the HSC problem followed in this work are presented in Section 3. Section 4 is dedicated to the solution strategy for applying multi-objective optimisation by mathematical programming and the use of a geographic tool for data treatment. The definition of the case study is presented in Section 5 with specific focus on parameters such as demand, energy sources, initial production plants and storage units, refuelling stations and roads. The multi-objective optimisation results for the national case are presented in Section 6 as well as the analysis and comparison of results for the regional and national scales. Finally, conclusions and perspectives are highlighted.

2. Literature review

Many studies use optimisation tools that could allow the generation of quantitative information when all the activities (nodes) of the supply chain are defined and integrated. Facility location problems have proven to be a fertile ground of operations research interested in modelling and design. In the case of a supply chain design, the network model assumes that demands arise, and facilities can be located, only on a network composed of nodes and links. In the mathematical formulation, mixed integer linear programming (MILP) formulations have been widely used.

2.1. *Mono-objective optimisation*

Mono-objective optimisation is still the most used approach considering an economic criterion. A largely used model is developed in Almansoori and Shah (June 2006): it determines the optimal design of a network (production, transportation and storage) for vehicle use where the network is demand-driven minimising the total daily cost. The model was applied to a Great Britain case study. The same authors extended the model in 2009 (Almansoori and Shah, Oct. 2009), to consider the availability of energy sources and their logistics, as well as the variation of hydrogen demand over a long-term planning horizon leading to phased infrastructure development as well as the possibility of selecting different scales of production and storage technologies. More recently, the technological diversity of the H_2 supply pathways together with the spatial-temporal characteristics is considered in (Murthy Konda et al., April 2011a) to optimise a large-scale HSC based on (Almansoori and Shah, June 2006) approach, including capacity expansion and pipeline features. An optimisation-based formulation is developed in Hugo et al. (Dec. 2005): it investigates different hydrogen pathways in Germany. The model identifies the optimal infrastructure in terms of both investment and environmental criteria for many alternatives of H_2 configurations. This model has been extended and considered as a basis for other works such as Li et al. (Li et al., Oct. 2008) for the case study in China. The development and use of a hydrogen infrastructure optimisation model using the H_2TIMES modelling framework to analyse hydrogen development in California to 2050 is described in Yang and Ogden (April 2013); in the same region, an economic model to assess several potential FCEV deployment rates is proposed in Brown et al. (April 2013). A multi-period MILP model (called SHIPMod) is presented in Agnolucci and McDowall (May 2013) presented: it optimises a HSC for hydrogen fuel demand scenarios in the UK, including the spatial arrangement of carbon capture and storage (CCS) units and the use of pipelines. This work concludes that assumptions about the level and spatial dispersion of hydrogen demand have a significant impact on costs and on the choice of hydrogen production technologies and distribution mechanisms.

2.2. *Multi-period optimisation with different approaches on demand*

All these models consider a deterministic demand but stochastic demand approaches are also available in the literature: Kim et al. (Sept. 2008) and Almansoori and Shah (2012) optimise the HSC finding the configuration that is the best for a given set of demand scenarios with known probabilities. The stochastic programming technique used is based on a two-stage stochastic linear programming approach with fixed recourse, also known as scenario analysis. More recently, an investigation (Liu et al., June 2012) focuses on the analysis of hydrogen demand from hydrogen FCEVs in Ontario, Canada for three potential demand scenarios (2015–2050). Dodds and McDowall (Feb. 2014) identified three key demand modelling decisions: the degree of car market segmentation, the imposition of market share constraints and the use of lumpy investments to represent infrastructure using the UK

MARKAL model. Dayhim et al. (April 2014) used a multi-period optimisation model taking into account the stochastic nature of the problem and the effect of uncertainty in the hydrogen production, storage and usage for the State of New Jersey.

2.3. *Multi-objective optimisation*

Also multi-objective optimisation models have been developed, Kim and Moon (Nov. 2008) applied bi-objective optimisation to minimise the cost and safety risk. The risk criterion is also optimised in Dagdougui (2011) and applied to the region of Liguria (North of Italy) and Morocco. A bi-criterion formulation that considers simultaneously the total cost and life cycle impact is proposed in Guillén Gosálbez et al. (2010). Eight environmental indicators (Sabio et al., 2011) are taken into account in a two-step method based on a combination of MILP multi-objective optimisation with a post-optimal analysis by principal component analysis (PCA) to detect and omit redundant environmental indicators. An approach is also developed in Sabio et al. (July 2010) in order to control the variation of the economic performance of the hydrogen network in the space of uncertain parameters examined the case study of Spain. All of these articles optimise the model through the familiar ε-constraint method. A dynamic computable equilibrium model with LCA method to forecast the development of the HSC and CO_2 emissions was also developed in Japan (Lee, 2014). Japan is one of most aggressive countries in developing a hydrogen economy, it plans to develop hydrogen highways for hydrogen-powered vehicles ((e.g. the launch of 'Mirai' Fuel Cell Sedan, sales in Japan on December 15, 2014, in the U.S. in autumn, and in Europe in September 2015 (Fuel, 2014)). Baseline results reveal that the positive impacts on hydrogen application sectors (FCEV, HFC and refuelling stations) are greater than hydrogen generation sectors (biohydrogen, steam reforming and electrolysis). A tri-objective optimisation model was developed by De-León Almaraz et al. (Nov. 2013), in this work, the total daily cost, environmental impact and relative safety risk of the HSC are simultaneously minimised and this model was extended to a real case study for the Midi-Pyrénées region in France treating a multi-period problem (De-Leon, 2014).

2.4. *Geographic studies*

Geographic tools are more and more used to design a HSC. The geographic information system (GIS) is a package that can be usefully integrated with a modelling system for supply chain management. The ArcGIS® software (developed by ESRI, Environmental Systems Research Institute) is a GIS used to organise, analyse and map spatial data. A typical GIS project contains an extensive database of geographic information, graphical capabilities of displaying maps with overlays pertaining to the company's supply chain activities. Literature review reveals that fewer researchers have used the spatial dimension to construct the infrastructure for hydrogen. Some examples of geographical approaches include the study of Ball et al. (2006) who developed the MOREHyS (Model for Optimisation of Regional Hydrogen Supply) approach of the energy system with the integration of geographical aspects in the analysis by the GIS-based method for Germany. This model identifies the cost-optimal way for constructing and implementing an (initial) hydrogen supply infrastructure as well as possible trade-offs between hydrogen production and electricity generation within a country-specific context (high degree of regionalisation). GIS is also used in Johnson et al. (Oct. 2008) for modelling regional hydrogen infrastructure deployment using detailed spatial data and applied the methodology to a case study of a potential coal-based hydrogen transportation system in Ohio with CCS to optimise the HSC for the entire state. More recently, Dagdougui (2011) highlighted that coupling a GIS component to a mathematical model could enhance and favours the exploitation of two different decision support systems and used a GIS to evaluate the use of renewables energies for hydrogen production. The MARKAL model has been applied to the UK with a GIS-based spatial model to represent the layout of hydrogen infrastructure (Yang and Ogden, April 2013). The design of pipeline systems based on GIS scenarios is presented in (Marcoulaki et al., Dec. 2012) (using stochastic optimisation and GIS) and in (Baufumé et al., April 2013) for a nationwide German hydrogen pipeline infrastructure assuming high penetration of hydrogen-fuelled vehicles for Germany in 2050. They calculate the preliminary layouts, dimensions and costs of nationwide capacitated pipeline networks transporting hydrogen from central production plants to refuelling stations. This scenario-based investigation relies on GIS data to describe production sites, local demand and preferred routes for pipelines. Transmission H_2 pipeline networks for France are analysed in André et al. (July 2014) by a backward heuristic approach. Results show that for the mid-term perspective and low market share, the trucks are the most economical options. However, for the long term, the pipeline option is considered as an economical viable option as soon as the hydrogen energy market share for the car fuelling market reaches 10%. In a previous work, the HSC for the Midi-Pyrénées region was analysed and mapped by the ArcGIS® software in De-Léon Almaraz et al. (2014). As highlighted in Agnolucci and McDowall (May 2013), few infrastructure optimisation studies have tested the sensitivity the spatial and temporal dynamics of demand. Current gaps in modelling for hydrogen systems are generally associated with the representation of the spatial distribution of hydrogen production and refuelling stations (Bolat and Thiel, June 2014) because of that the use of GIS is highly recommended and can help to identifying specific conditions for different geographic scales. The HSC design depends on national or regional specific conditions and is subject to local territorial constraints, such as the specific transportation network, population density, available resources or local policies.

2.5. *Objectives of the study*

Our work is intended to analyse the effect of changing the approach spatial scale from regional national when homogeneous demand is given for the studied territories. The current paper is a part of a larger study (De-Leon, 2014) that designs a HSC through multi-objective, multi-period optimisation in a long time horizon (2020–2050). The objective of this work is twofold: first, to test the robustness of the mathematical model and methodology proposed in De-Leon (2014) initially applied to a regional case and, in this paper, adapted to a national one (which includes the region previously treated) and, secondly, to examine the consistency of the results and to identify the main difficulties when different geographic scales are studied. To our knowledge, in the dedicated literature, such analysis has not yet been done. This aspect constitutes the originality of this work. Until now, it is assumed that the mathematical model can be applied generally without specifying the obstacles that may arise when a new geographic scale.

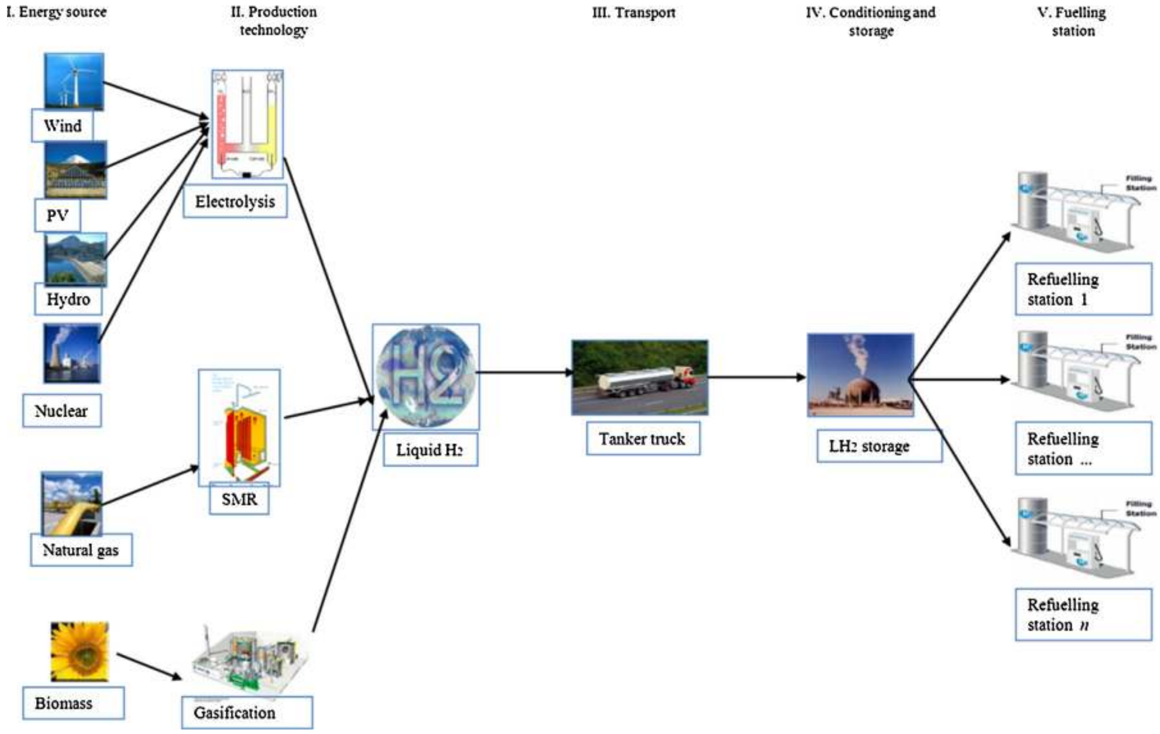

Fig. 1 – The HSC studied for France (De-Leon, 2014).

This study seems mandatory since the multi-scale analysis could offer interesting information for the decision maker.

3. Formulation of the HSC problem

In this section, the problem statement, assumptions and objectives of the HSC are presented to study a new geographic scale. The considered items of the HSC are mentioned to establish the general structure of the network. As this work intends to compare results of the regional case with those of the national level, the same optimisation approach was used for both cases, only differing in the way to treat geographic data for the case study presented here.

The following questions are addressed to define the problem:

- what is the best option to produce and store hydrogen in France?
- which are the main product flow rates and transportation modes to supply H_2 to the demand centre?
- is it possible to find competitive targets for a national case compared to a regional one?
- which are the main differences when different geographic scales are evaluated?

3.1. *Objectives*

- The first objective of this work is to design a five-echelon HSC (energy source, production, transportation, storage and refuelling station) using multi-objective optimisation, minimising the cost, the environmental impact and the safety risk for a multi-period problem.
- The second objective is to examine the robustness of the developed methodology and the impact of the territory discretisation and economies of scale for two HSCs.
- The third objective is to identify the main difficulties in the model adaptation when different geographic scales are studied for the HSC.
- The last objective is to use a geographic tool before and after optimisation to have a more precise snapshot of the HSC considering geographic constraints.

3.2. *Assumptions*

The following assumptions are taken into account:

- a deterministic demand of hydrogen for the transportation system (particular and light-good vehicles and buses) is considered;
- the computed risk associated with production plants, storage facilities and transportation modes are assumed to be independent of the considered demand scenario.
- the model is assumed to be demand driven.

3.3. *Mathematical model*

In the proposed formulation, hydrogen can be delivered in specific physical form *i*, such as liquid, produced in a plant type with different production technologies *p* (i.e. SMR, gasification and electrolysis); using energy source *e* (i.e. natural gas, biomass, nuclear, solar, wind and hydro powers) distributed by a specific type of transportation mode *l* (i.e. tanker truck) going from the location *g* to *g'* referred as regions; such that *g'* is different than *g*; for storage facility type *s*, different storage sizes *j* (mini, small, medium and large) are involved. Once more, the administrative segmentation has been taken into account, so that the sub-division level that is considered in this work is the regional one (21 French regions are involved). In future works, the gaseous physical form, the transportation by pipeline and the use of carbon capture and store can take place (see Fig. 1).

The mathematical formulation used in this paper results from the progressive development of a tool for designing the HSC by the validation of previous works and the improvement of a base model. It was first inspired from the model of Almansoori and Shah (Almansoori and Shah, June 2006), extended from a mono-objective to a multi-objective optimisation approach in (De-León Almaraz et al., Nov. 2013) where constraints related to environmental impact and safety risk (as carried out in Kim and Moon, Nov. 2008; Kim et al., June 2011) were introduced, and the existence of antagonist criteria resulted in different configurations for the HSC, the model remained as mixed integer linear programming (MILP). More recently in De-Leon (2014), a multi-period optimisation approach was carried out with the objective of minimising the criteria on the entire time *horizon t*. Another specific feature for this case is the integration of renewable energy constraints *e*.

For reasons of brevity, not all the equations are presented here but mass balance, production, transportation and storage constraints can be found in De-León Almaraz et al. (Nov. 2013) where different constraints features (i.e. equality or inequality, bounds) are easily appreciated. In this paper only the objective functions are presented.

3.3.1. *Economic objective function*

The first criterion to be optimised is an economic function defined as the total daily cost (TDC) of the hydrogen supply chain. It is obtained by the combination of the capital and operational cost terms from production plants, storage facilities and transportation units:

$$\mathrm{TDC} = \sum_{t} \frac{\mathrm{FCC}_t + \mathrm{TCC}_t}{\alpha \mathrm{CCF}} + \mathrm{FOC}_t + \mathrm{TOC}_t + \mathrm{ESC}_t \quad (1)$$

The first term of the right-hand-side of this objective function (facility and transportation capital costs, FCC_t and TCC_t in the time period *t*) is divided by the network operating period (α) and the annual capital charge factor-payback period (CCF) to find the cost per day in US dollars. This result is added to the facility and transportation operating costs (FOC_t, TOC_t) and to the transportation cost of the energy source (ESC_t).

3.3.2. *Total global warming potential*

The global warming potential (GWP) is an indicator of the overall effect of the process related to the heat radiation absorption of the atmosphere due to emissions of greenhouse gases (CO_2-eq) of the network (Utgikar and Thiesen, June 2006). Three terms are associated: the total daily GWP resulted from production (PGWP, in g CO_2-eq d^{-1}), the SGWP which is the GWP of storage units and the TGWP related to transportation. By combining these environmental terms, the total daily GWP is calculated per time period *t* as follows:

$$\mathrm{GWPTot}_t = \mathrm{PGWP}_t + \mathrm{SGWP}_t + \mathrm{TGWP}_t \quad (2)$$

3.3.3. *Total inherent risk index*

Kim and Moon, Nov. 2008; Kim et al., June 2011 have developed expressions to evaluate the total risk of production/storage facilities and transportation units (TPRisk, TSRisk and TTRisk respectively) where the relative risk of hydrogen activities is determined by risk ratings calculated based on a risk index method. The TPRisk considers the risk of the production plants of type *p* producing product *form i* in grid *g*. A population weight factor in *g* in which a production or storage facility is located is also reflected. The TSRisk is related to the potential risk of storage facilities of type *s* and the TTRisk is associated to transportation risk given by the number of transport units going from *g* to *g'* ($\mathrm{NTU}_{ilgg't}$) and the risk between grids. An inherent risk factor is taken into account for production, storage and transportation (also the facility size has a weight factor). The total relative risk index (TRRI) is given by Eq. (3):

$$\mathrm{TRRI}_t = \mathrm{TPRisk}_t + \mathrm{TSRisk}_t + \mathrm{TTRisk}_t \quad (3)$$

For the application of the model to the national case study, no major changes are required. The problem is captured in an MILP framework. All continuous and integer variables must be non-negative. It must be mentioned that new electrolysis plants that use renewable energy are allowed to be implemented when renewable energy *e* is available in the region *g*. The exportation of renewable energy between regions *g* to *g'* is not considered for France. A multi-period problem is studied (2020–2050).

4. Solution strategy

4.1. *Multi-objective optimisation strategy*

The problem is solved using multi-objective optimisation based in the ε-constraint method. In the ε-constraint method, introduced by Haimes et al. (July 1971) all but one objective are converted into constraints by setting an upper or lower bound to each of them, and only one objective is to be optimised (Liu and Papageorgiou, April 2013). By varying the numerical values of the upper bounds, a Pareto front can be obtained. The model is formulated within GAMS environment (Brooke et al., 1988) and solved using CPLEX 12. The global model can be formulated in a concise manner as follows:

$$\begin{array}{l} \textit{Minimise}\ \{TDC\} \\ \text{Subject to}: \\ h(x,y) = 0 \\ g(x,y) < 0 \\ x \in R^n,\ y \in Y = \{0,1\}^m,\ z \in Z^+ \\ \text{Risk} \le \varepsilon_n (n = 0, 1, 2, \ldots, N) \\ \text{TotalGWP} \le \varepsilon_m (m = 0, 1, 2, \ldots, M) \end{array} \quad \left\{ \begin{array}{l} \text{Demand satisfaction} \\ \text{Overall mass balance} \\ \text{Capacity limitations} \\ \text{Distribution network design} \\ \text{Site allocation} \\ \text{Non-negativity constraints} \end{array} \right\}$$

The objective of this formulation is to find values of the operational $x \in \mathbb{R}^n$, and strategic $y \in Y\{0,1\}^m$ and $z \in \mathbb{Z}^+$ decision variables, subject to the set of equality $h(x, y) = 0$ and inequality constraints $g(x, y) < 0$. In this model, the continuous operational variables concern decisions dedicated to production, storage and transportation rate, whereas the discrete strategic variables capture the investment decisions such as the selection of activity types and transportation links.

All costs, emissions and risk equations occur as linear functions of the associated decision variables levels. That means the production, storage and transportation costs, GWP and safety risk levels are linear values of the associated decision variables. The solution consists of a Pareto front composed of solutions that represent different possibilities of supply chain configurations.

To make the best choice among these compromise solutions, multi-criteria decision making methods can be used. One of them is TOPSIS (technique for order preference by similarly to ideal solution). The basic concept of this method is that the selected alternative should have the shortest distance from the positive ideal solution and the farthest distance from the negative ideal solution in a geometrical sense. TOPSIS

Table 1 – ArcGIS® database layers.

Layer	Layer description	Source
Pre-optimisation data treatment		
Regional boundary	21 regions	(IGN, 2013)
Initial conditioning centres	Current Air-Liquide and Linde and Praxair sites.	(PHyRENEES, 2009)
Initial production plants	Current Air-Liquide and LINDE plants.	(PHyRENEES, 2009)
Refuelling stations	Current stations. Minimum distance between refuelling stations = 300 km	(Esso, 2013)
By-product plants	Chloralkali electrolysis	(Arkema, 2013; UIC, 2013)
Roads	Only motorways and national roads are considered	(IGN, 2013)
Hydro sites	Approximate location for small sites	(EDF, 2011)
Biomass	Biomass installed capacity in 2012	(Observ'ER, 2013)
Nuclear centrals	Classified in three sizes (less than 2000 MW, from 2000 to 4000 MW or more than 4000 MW)	(EDF, 2011)
Wind sites	Precise GPS coordinates were not collected	(Rte, 2013)
PV Sites	Precise GPS coordinates were not collected	(Rte, 2013)
Post-optimisation data treatment		
New layers	Constraints	
New conditioning centres	Close to the production plants or the refuelling stations	
New SMR plants	Next to the main roads	
New electrolysis plants	Near energy sources and in the case of exporters, next to the main roads	
	For small decentralised units, PV and wind electrolysers (for which no precise GPS coordinates are known): near to refuelling stations and main roads	
New gasification plants	Near biomass centres and main roads	
Transportation links	Using main roads	

is attractive because it requires only a subjective input from decision makers: the assignation of weights for each objective. This may explain why TOPSIS is very popular in engineering applications and ecodesign process. M-TOPSIS (Ren et al., 2007) a variant of TOPSIS, has been adopted in this work. The main change introduced by in M-TOPSIS method is to avoid rank reversals and then solve the problem on evaluation failure when alternatives are symmetrical. These two problems often occur in the original TOPSIS version. In the studied case, the results of the solution selected by M-TOPSIS, are discussed. The whole Pareto front can yet offer interesting solutions that can be explored by the decision maker according to other criteria (e.g. engineering practices, environmental policies, budget targets, etc.).

4.2. *Geographic approach*

One of the main aims of this work is to have a more precise snapshot of the HSC for a given territory. Optimisation results are represented within a specialised geographic tool. The ArcGIS® software is used to perform data treatment before and after optimisation.

In a GIS analysis project, an analyst faces a variety of tasks that can be grouped into four basic steps (Booth and Mitchell, 1999):

1. To convert a question, such as "where is the best place for a new production plant?" or "how many potential refuelling stations are near a particular energy source?" into a GIS database design and an analysis plan. This involves breaking the question into logical parts, identifying what layers of data will be needed to answer each part and developing a strategy for combining the answers to each part of the question into a final answer.
2. To create a database that contains the geographic data required to answer the questions. This may involve digitising existing maps, obtaining and translating electronic data from a variety of sources and formats, making sure the layers are of adequate quality for the task, making sure the layers are in the same coordinate system and will overlay correctly, and adding items to the data to track analysis result values. Personal workspaces of file based data and personal geo-databases are used to organise project GIS geo-databases. These layers are listed in Table 1 in the *pre-optimising* data section. The decision variables are located following defined constraints that are listed in the same table in the *post-optimisation* data section.
3. Data analysis. This usually involves overlaying different layers, querying attributes and feature locations to answer each logical part of the question, storing the answers to the logical parts of the question, and retrieving and combining those answers to provide a complete answer to the question.
4. To communicate the results of the analysis. Maps, reports, and graphs are all used, often together, to communicate the answer to the question.

A spatial-based approach is used to display the geographic and demographic data of France and the HSC resulted from the optimisation approach. In this work, two stages could be defined for using the GIS: pre- and post-optimisation (see Fig. 2).

In the pre-optimisation stage, ArcGIS® is used to create layers to locate the coordinates of existing conditioning centres, hydrogen production plants, by-product sites, refuelling stations, roads, hydro sites, biomass centres and nuclear centrals. All these elements are listed in Table 1. The energy sources layer is produced using the GPS coordinates in Arc Map 10.2. Roads and geographical data maps are taken from the French National Geographic Institute (IGN) (IGN, 2014). To calculate the delivery distances over the road network, an average distance between the main cities is considered (only national roads).

In the post-optimisation stage, the decision variables (energy source sites, production and storage facilities with

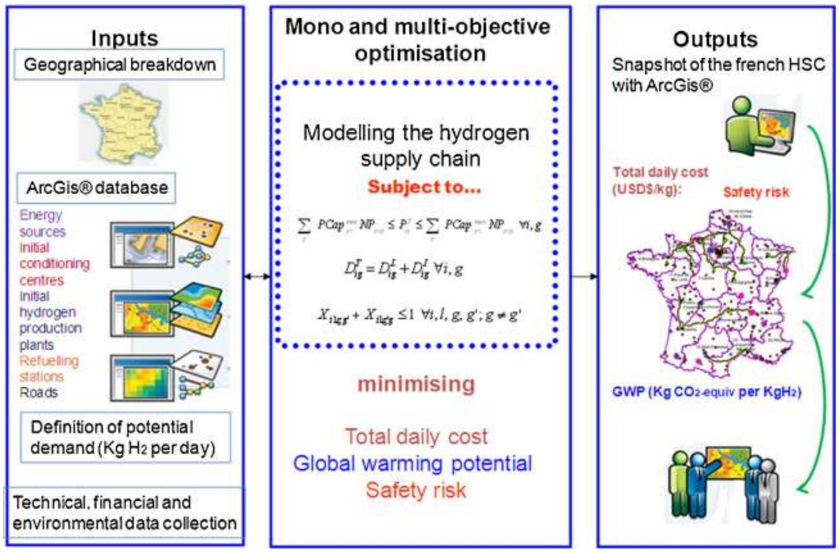

Fig. 2 – Methodology framework for the French case study.

different sizes, refuelling stations and flow rate links) are to be located in the final snapshot. The locations (districts or regions) where new facilities are to be established are given as optimisation results but, the feasibility of the proposed configuration still depends on the geographic constraints. ArcGis® is used to validate the best place for new hydrogen production plants, storage units, refuelling stations and proposes the road to be used based respecting the current conditions of the studied territory.

Fig. 3 shows the geographic data-flow before and after optimisation. The GIS information to be introduced manually as parameters to be used in the MILP model is visualised in green. The blue rectangles represent auxiliary GIS layers related to territory division, road network and location of energy sources. Technical, financial and environmental data are imported from Excel data bases as well as the calculation of the hydrogen demand to the MILP model which is represented in red (the multi-objective optimisation is done at this stage). Results (presented in purple) are displayed in Excel and the potential configurations plotted on the Pareto front are to be evaluated through M-TOPSIS. The chosen network is mapped in ArcGIS and is taken as a basis for the already built layers following the specific real geographic constraints. These conditions allow to verify the feasibility of the selected HSC and to propose a snapshot easy to read. An automatic coupling of ArcGIS and GAMS remains strongly recommended. The model inputs and outputs are briefly described in the next section.

4.3. *Model inputs*

The input data to be introduced in GAMS involve:

- demand volume,
- energy source availability and location,

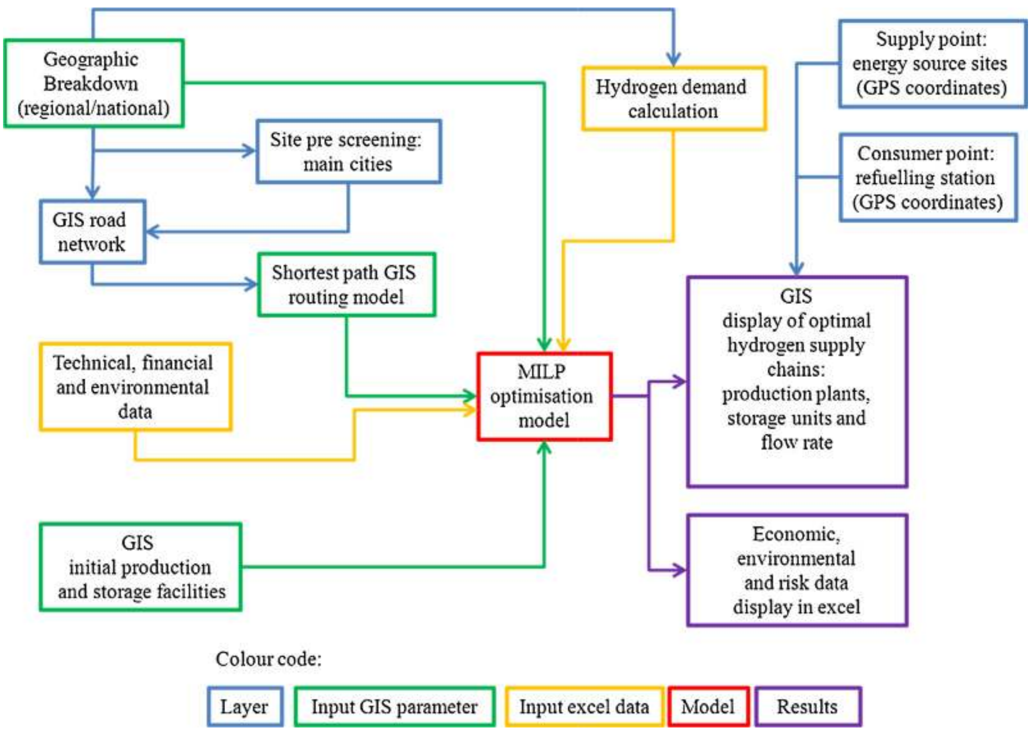

Fig. 3 – Model flow chart.

- initial number of production plants and storage facilities,
- shortest distances between main cities (national roads; intra-city delivery of hydrogen is not considered in this work),
- existing refuelling stations,
- techno-economic, environmental and risk data.

4.3.1. *Geographic breakdown*

The territory under study for the HSC implementation is divided into grids, regions or districts in which production and storage units could be located according the scale and decision maker preferences. This division could affect the transportation links, the allocation of the main transportation routes will depend of the supply–demand potential sites which will be entered in the MILP model.

4.3.2. *Site pre-screening and GIS transportation network*

Models of hydrogen delivery need distances over the road networks between the supply points, the production and conditioning sites and the demand centres. A very important issue is to select an adequate geographic breakdown to guarantee the interconnection points exist; the GIS approach allows finding easily the current transportation infrastructure. To optimise the delivery distances over the road network, the shortest distance between the supply and demand points is considered as input in the optimisation model (see Fig. 3). Yet, it does not allow locating precisely the involved units and delivery paths because only potential sites could be proposed.

4.3.3. *Technical, financial and environmental data*

Several data sets are necessary to design the HSC including demand volume, availability of energy sources, initial number of production plants and storage facilities, techno-economic, environmental and risk data of the components in the HSC. These parameters are presented in Appendix A and De-Leon (2014).

4.3.4. *Hydrogen demand calculation*

The potential demand for hydrogen is computed according to Eq. (1) as in the works of Almansoori and Shah (June 2006) and Murthy Konda et al. (April 2011b). A deterministic demand of hydrogen for FCEV is considered, including fleets such as buses, private and light-good-vehicles at 2012 levels.

$$D_{ig}^{T} = FE.d.Qc_g \tag{3}$$

where the total demand in each district (D_{ig}^{T}) results from the product of the fuel economy of the vehicle (*FE*), the average total distance travelled (*d*) and the total number of vehicles in each district (Qc_g) (see Table B1).

4.4. *Model outputs*

Model outputs are the design and operational decisions for the HSC. Design decisions are based on the number, type, capacity, and location of production and storage facilities. More precisely, they involve the number and type of transport units required as well as the flow rate of hydrogen between locations and the number of refuelling stations. Operational decisions concern the total production rate of hydrogen in each region, the total average inventory in each region, the demand covered either by imported hydrogen or by local production. These results are exported from GAMS to Excel and new geographic layers are created in ArcGIS® 10.2 to display the HSC locating the new production and storage sites. The flow rate links are also defined and diverse geographic layers are necessary to create the maps or snapshots; the potential sites are located following the geographic restrictions (see Table 1).

5. Case study

France is divided into 21 regions (metropolitan France) without the territorial region of Corsica (see Fig. 4). Three different production processes are evaluated: SMR, electrolysis and biomass gasification. Hydrogen is assumed to be liquefied before being stored or distributed. Liquid hydrogen (LH_2) is stored in super-insulated spherical tanks then delivered via tanker trucks. For this case, the parameters list is presented in Appendix A.

5.1. *Demand scenario*

A deterministic demand of hydrogen for FCEV is considered for the French case, including fleets such as buses, private and light-good-vehicles at 2012 levels. A specific market scenario is studied following the prospective conducted by McKinsey (2010) and Bento (2010). The proposed scenario assumes that 1% of the vehicles market in France at 2012 levels would be covered by FCEVs in 2020. The potential demand of H_2 in each region is obtained from the product of the fuel economy (fuel efficiency) of the FCEV, the average total distance travelled and the total number of vehicles in each region (i.e. 160 t per day in 2020). The consecutive periods are calculated in the same way, on the market shares of 7.5% in 2030 (1202 t per day), 17.5% in 2040 (2805 t per day) and 25% in 2050 (4007 t per day) (see Table A1).

5.2. *Energy sources*

Four renewable energy sources are considered according to:

- the projection of solar and wind energies to 2017 (Rte, 2013);
- the biomass installed capacity in 2012 (Observ'ER, 2013) (see Fig. 4);
- hydropower capacity (EDF, 2011). Only “run-of-river” facilities are taken into account with two ranges for plant sizes: small (50-100 MW) and medium (100-250 MW) (see Fig. 4).

The current installed capacity expressed in MWh per day is available from databases for the geographic division in regions, but the information level is not as detailed as in the Midi-Pyrénées case (De-Leon, 2014). From the aforementioned sources, it must be highlighted that some differences regarding the amount of energy sources in the Midi-Pyrénées region exist compared to the national study. The order of magnitude leads to less power availability in PV and wind energies (−13.6% and −37% respectively) and to an increase in hydropower (76%). We are aware that this difference could influence the results. No correction was yet performed in order to maintain the same orders of magnitude for all the regions.

For renewable energy sources (RES), an average working horizon of 1200 h/year is considered for photovoltaic panels and 2500 h/year for wind energy (Salingue, Sept. 2012). For hydropower “run-of-river” plants, a working period of 3500 h/year is considered based on Schema (2012). The

Fig. 4 – Elements of the HSC in France before optimisation in ArcGIS®.

potential use of nuclear electricity is also considered as an energy source for the electrolysis process (nuclear sites are displayed in Fig. 4). However, the commercial production technology used to produce H_2 today is the SMR and that is why the comparison of this process with those using renewable energy appears relevant.

5.3. *Production plants and conditioning centres*

Ten production plants using mostly SMR are already installed in France (Phyrenees, 2009) and fifteen conditioning centres (see Fig. 4). In the case of the by-product plants, its potential capacities are not considered by the moment because of the lack of information regarding the investment cost necessary to add purification steps for hydrogen in these plants. However, they are located in the territory to see potential sites for future facilities.

5.4. *Roads and refuelling stations*

For roads, only motorways and national roads are considered (IGN, 2014) in Fig. 4. More than 12000 refuelling stations exist in France. Their location was carried out from (Esso, 2013) data base using the GPS coordinates locating only 300 of these units in ArcGIS® because of graphic readability considering stations close to the main roads, the other stations have been filtered and can be added. The Directive of the European Commission (European, 2013) on the deployment of infrastructure for alternative fuels, recommend a H_2 refuelling station every 300 km.

6. Results

The optimisation runs were performed with a Pentium (R) Dual-core CPU E6600 @ 3.06 GHz processor machine. Multi-objective optimisation results for the French HSC are

Table 2 – Pay-off table obtained by the mono-objective optimisations for all periods.

Minimising	Cost	CO_2	Risk
Average cost per kg H_2 ($)	**3.4**	7.4	6.5
Average kg CO_2-equiv/kg H_2	11.0	**2.2**	4.9
Total risk (units)	7435	14229	**1598**

explained in this section starting with the analysis of the multi-objective optimisation results followed by the comparison of different territorial scales to verify the discretisation impact and the influence of the economies of scale.

6.1. *Multi-objective optimisation (ε-constraint method)*

As a preliminary stage, three independent mono-objective optimisations were solved to obtain, for each objective, the utopia and nadir points so that the ε-constraint method can be applied (see Table 2). Discretisation of the total *risk* can be divided into five levels (ε-points) to make the interpretation easier: low risk is lower than 4600 units, moderate risk lower than 4800, medium risk, 7900, significant risk lower than 11,000 and high risk lower than 14,200. Similarly, 10 ε-points are defined for GWP (2.2, 3.1, 4.1, 5.1, 6.1, 7.1, 8, 9, 10 and 11 average kg CO_2 per kg H_2). Then, the objective function related to the total daily cost has to be minimised while the GWP and total *risk* are considered as inequality constraints.

The solution consists of a Pareto front composed of solutions equivalent to supply chain configurations presented in Fig. 5. It can be observed in this figure that moderate-to-high risk options are very close. The 46 solutions in the Pareto front are evaluated via M-TOPSIS analysis with the same weighting factor for cost, safety and environmental factors (see Appendix B). The resulting HSCs are shown in Figs. 6 and 7 and the decision and operational variables are displayed in Table 3.

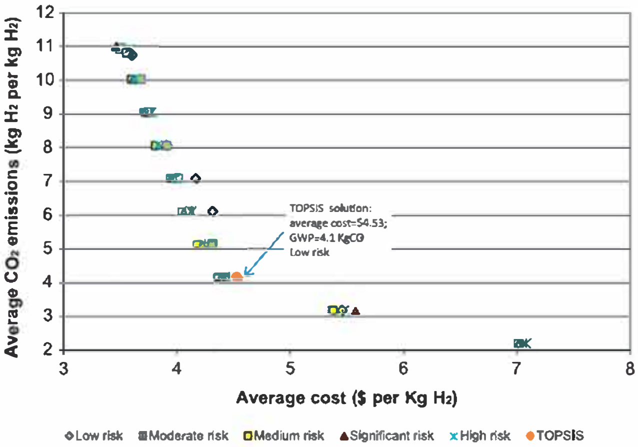

Fig. 5 – Pareto solutions for the multi-objective optimisation to the French case Pareto solutions for the multi-objective optimisation to the French case.

According to these results for the national case, the future HSC involves 21 production plants in 2020 (see Fig. 6, year 2020) from which 10 are already installed and 11 wind-electrolysis plants are established (38% of the hydrogen is produced via electrolysis in this period). To cover the demand, this network uses nine tanker trucks to deliver liquid H_2 to medium storage facilities. This option involves a cost of $6.5 per kg H_2, an environmental impact of 7.5 kg CO_2 per kg H_2 and a low risk. It must be emphasised that even if SMR plants are used in this period, the cost remains relatively high because of the initial investment in electrolysis plants and new storage units. On average 30% of the total demand is imported from one region to another.

By 2030 (Fig. 6—2030), a mix of production technologies such as biomass gasification, wind electrolysis and SMR is involved. Gasification produces 86% of the total demand, SMR 11% and electrolysis 3%. This option leads to a cost of $6.1 per kg H_2, an environmental impact of 4.7 kg CO_2 per kg H_2

Table 3 – Multi-objective optimisation results of the hydrogen supply chain for France.

Year	2020	2030	2040	2050
Demand (t per day)	160.30	1202.24	2805.23	4007.47
Number of total production facilities	21	26	31	31
Number of new production facilities	11	5	5	0
Number of total storage facilities	37	63	94	127
Number of new storage facilities	22	26	31	33
Number of transport units	9	83	104	140
Capital cost				
Plants and storage facilities (10^6 $)	1352	11,995	11,977	2031
Transportation modes (10^3 $)	4500	41,500	52,000	70,000
Operating cost				
Plants and storage facilities (10^3 $ per day)	728.8	4417.1	10284.1	14675.9
Transportation modes (10^3 $ per day)	6.0	78.7	95.1	129.4
Total operating cost (10^3 $ per day)	734.9	4495.8	10379.2	14805.2
Total network cost (10^3 $ per day)	1049.7	7311.6	13250.1	15457.1
Cost per kg H_2 ($)	6.5	6.1	4.7	3.9
Production facilities (t CO_2-equiv per day)	1072.7	4618.0	9037.9	12859.5
Storage facilities (t CO_2-equiv per day)	112.9	846.4	1974.9	2821.3
Transportation modes (t CO_2-equiv per day)	13.9	182.5	217.0	293.6
Total GWP (t CO_2-equiv per day)	1199.4	5646.8	11,229.8	15,974.4
Kg CO_2-equiv per kg H_2	7.5	4.7	4.0	4.0
Production facilities	24	54	83	83
Storage facilities	105	253	435	595
Transportation modes	46	443	452	601
Total risk (units-level)	174	750	971	1280

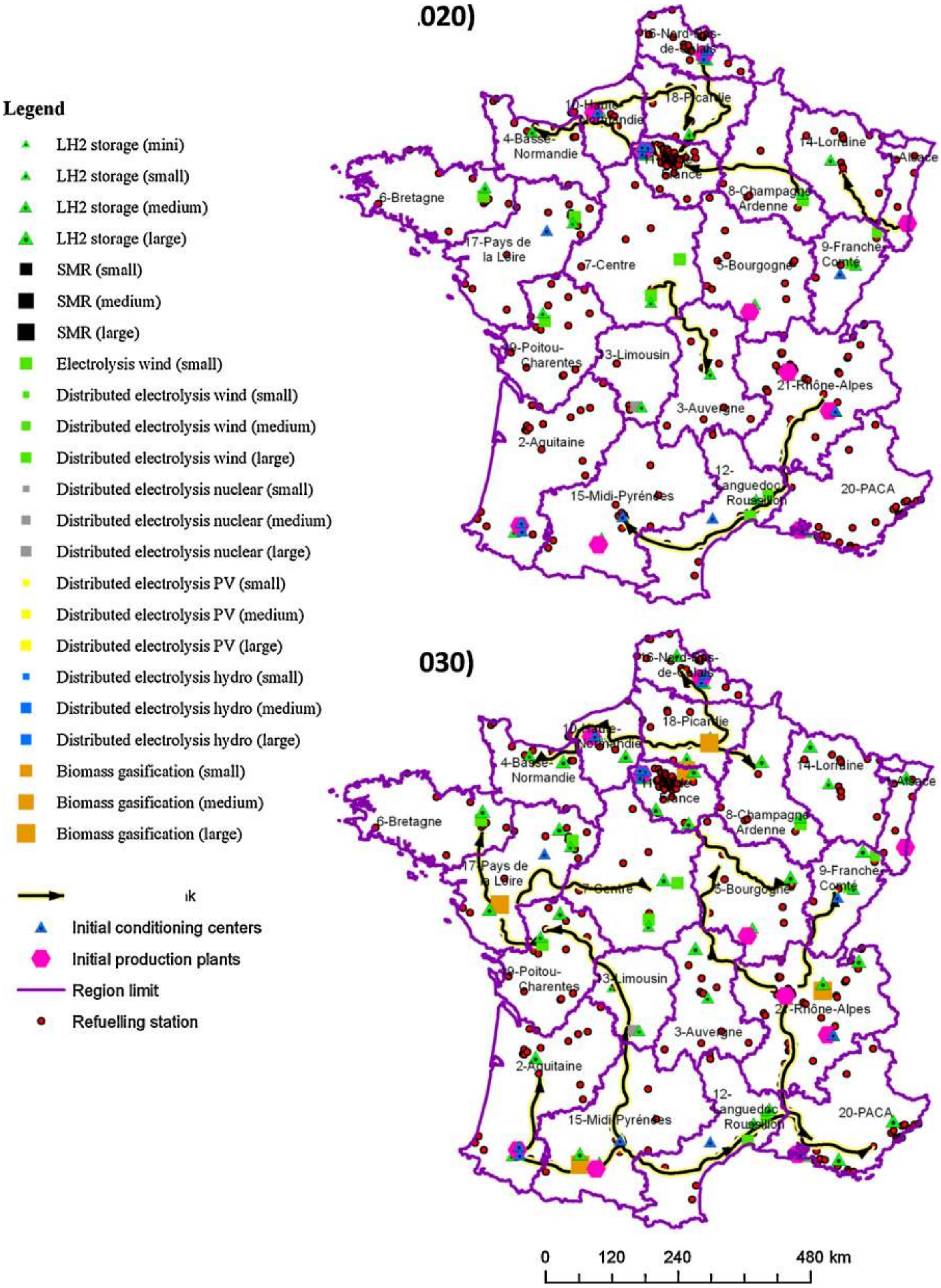

Fig. 6 – Network structure of liquid hydrogen distributed via tanker trucks in 2020–2030.

with a low risk. The cost slightly increases because of the investment on five new gasification production plants and 26 storage units, but at the same time, an important decrease in the GWP results from this configuration (from 7.5 kg CO_2-equiv per kg H_2 in 2020 to 4.7 in 2030).

By 2040 and 2050 (Fig. 7), biomass gasification produces more the 97% of the total demand. In 2050, the chosen solution involves an average cost of \$3.9 per kg H_2, an environmental impact of 4 kg CO_2 per kg H_2 (as in 2040) and a low risk.

6.2. *Comparison between regional and national cases*

All the results concerning the multi-objective optimisation for regional (De-Leon, 2014) and national cases are summarised in

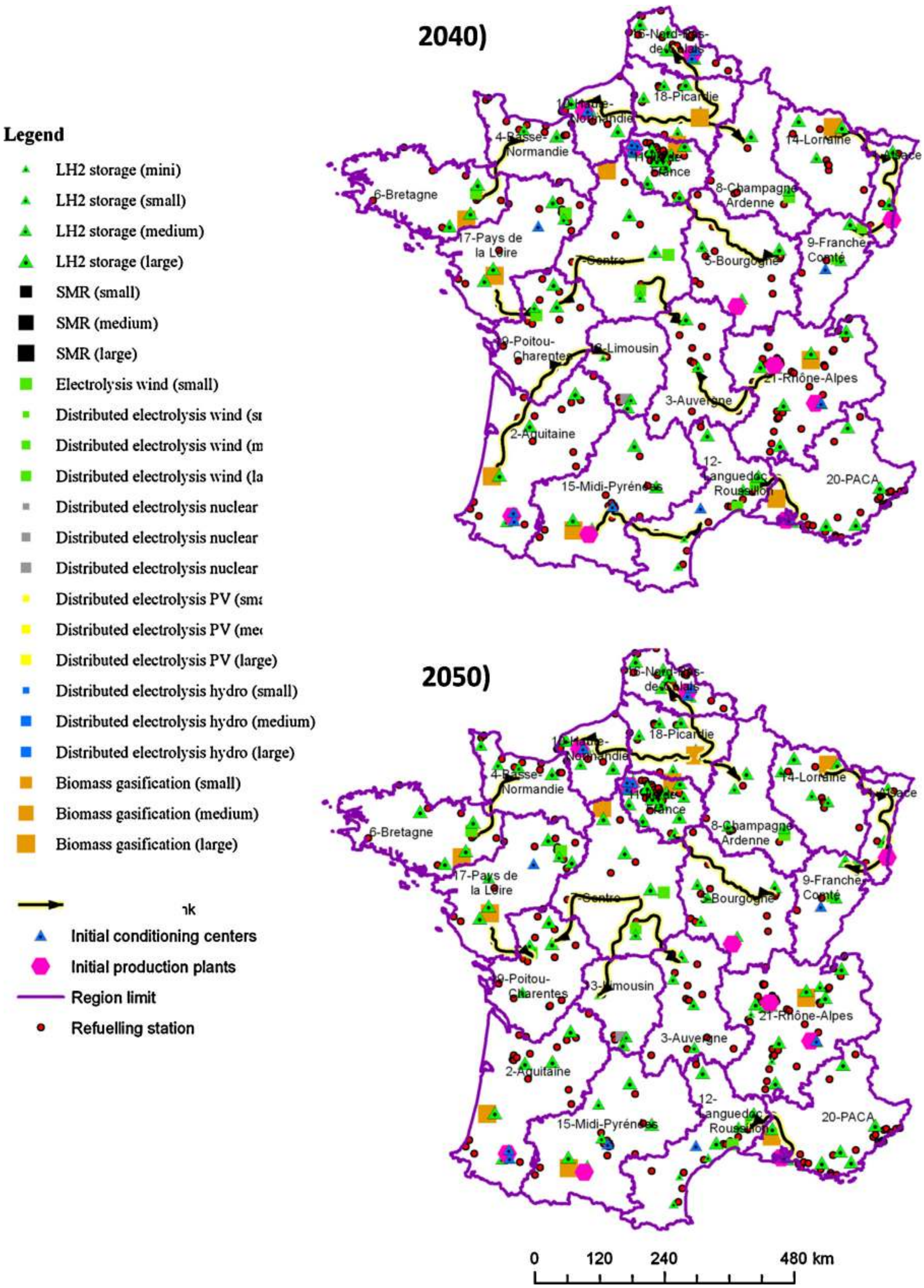

Fig. 7 – Network structure of liquid hydrogen distributed via tanker trucks in 2040–2050.

Table 4. For both cases a deterministic demand of hydrogen for FCEV is considered, including fleets such as buses, private and light-good-vehicles at 2010 levels. Midi-Pyrénées demand represents 5% of the national French demand at 2050 (198 vs 4007 t per day respectively). In the regional case, the best results are found using lexicographic and ε-constraint methods in four mono-period problems following sequential optimisation. In Midi-Pyrénées, the HSC for the 2020 period results in low GWP emissions and risk but the cost is high (\$13.9 per kg H_2). In the national case, the application of global (multi-period) ε-constraint method was used.

The national and regional cases are compared to analyse the statistics and problem sizes (see Table 4). The number of constraints is similar in both cases because in one case

Table 4 – Multi-objective optimisation results for regional and national cases.

	Solution strategy	Midi-Pyrénées (De-Leon, 2014)	France
2020	Cost per kg H_2 ($)	13.9	6.5
	kg CO_2 per kg H_2	2.1	7.5
	Total risk (units)	37.5	174
2030	Cost per kg H_2 ($)	9.1	6.1
	kg CO_2 per kg H_2	2.1	4.7
	Total risk (units)	102	750
2040	Cost per kg H_2 ($)	8.1	4.7
	kg CO_2 per kg H_2	2	4
	Total risk (units)	206	971
2050	Cost per kg H_2 ($)	7.3	3.9
	kg CO_2 per kg H_2	1.9	4
	Total risk (units)	277	1280
Statistics			
Number of constraints	205,057	175,667	
Number of single variables	31,255	31,943	
Number of discrete variables	11,088	11,088	
Computational time to build the whole Pareto front (h)	18	48	

there are 22 districts for the region and 21 regions for the country, then, the number of potential locations is very close following for both of them a multi-period approach with four time periods. The computational time increased from the Midi-Pyrénées case to the French case because more ε-points were calculated for the last one to obtain the Pareto front.

One focus of this paper was the feasibility to find competitive targets for a national case compared to a regional study. The considered targets to be reached for hydrogen cost are related to current gasoline and diesel prices. In France, the gasoline price (unleaded 95) on July 2013 was US$7.73 per gallon) and for Diesel US$6.73 per gallon) (Drive, 2013). Let us remember that 1 kg of hydrogen is approximately equivalent to one gallon of gasoline based on lower heating value energy content. H_2 cost must be lower than 5.3 US$/kg in the periods 2020 and 2030 (Ball and Wietschel, 2008), and less than US$7.11 per kg in 2050 (European, 2008).

Concerning the environmental impact, there are plans for further reductions of tank-to-well emissions by 2020 to 95 g/km (equivalent to 113 g CO_2/km in a well-to-wheel perspective) (McKinsey, 2010; Boretti, March 2011). Hydrogen should be below 9.5 kg CO_2/kg H_2 to offer an advantage. In the regional case, 2.1 kg CO_2/kg H_2 in 2020 are emitted (using RES with electrolysis process), this amount is 7.5 kg CO_2/kg H_2 in the same year for the national study because France has already some installed production capacity in SMR and gasification plants. Some of these plants have been considered in the HSC for France in 2020, resulting in a higher environmental impact but this configuration remains an environmental benefit with regard to current fossil fuels and its impact will be reduced in the next time periods.

For the studied scenarios (see Table 5), we can conclude that the multi-objective optimisation treated in the national case offers a good trade-off among the three objectives; in economic terms, this HSC is almost competitive since 2020 with low risk and a medium to low digressive environmental impact. This configuration resulted in production via biomass gasification (producing 97% of the total demand in 2050) followed by SMR and wind-electrolysis. This is mostly a decentralised network because only the 30% of the total demand is exported from one region to other. From an economic point of view, this is a very optimistic scenario compared to the Midi-Pyrénées case where the target is reached only in the latest maturity date of 2050 but this region offers a huge benefit in CO_2 reduction and a decentralised network using renewable energy sources (i.e. wind, hydro and PV) though electrolysis production.

For France, the production mix starts with the use of SMR in 2020 and the installation of different types of technologies that explains why the total GWP is higher than in Midi-Pyrénées study. This impact decreases over the time horizon and reaches its minimal value by 2050 with 4 kg CO_2/kg H_2 (using biomass gasification).

Besides, the risk is mainly associated to transportation. The degree of centralisation can be measured here by the percentage of imported demand. A more centralised network resulted in the national case with around 30% of hydrogen to be transported. Because of the cost impact in the French case study, transportation via pipeline could represent an interesting option to be analysed in next studies. This hypothesis is also based on the work of (André et al., July 2014) which concludes that for the long term, the pipeline option is considered as an economical viable option as soon as the hydrogen energy market share for FCEV market reaches 10%. Concerning the risk, it was surprising that for the national case that results allow to locate plants even in very densely populated regions (e.g. Ile de France). This point needs to be studied in detail before the next optimisations to verify if the risk weight given to the region size is adequate.

The geographic representation of the snapshots for both cases is presented in Fig. 8. The Midi-Pyrénées region is highlighted to show the different detail level between scales.

The region/district size represents an important issue for the flow rate of liquid hydrogen and the use of trucks because the tanker truck capacity per trip is 3500 kg of H_2 and in the Midi-Pyrénées case study (divided in districts), the demand per district was lower than the 3.5 t/day in the first time periods, then, instead to established a distribution link, the optimiser chose a decentralised production (see Fig. 8a). This result could change if other transportation modes are assessed.

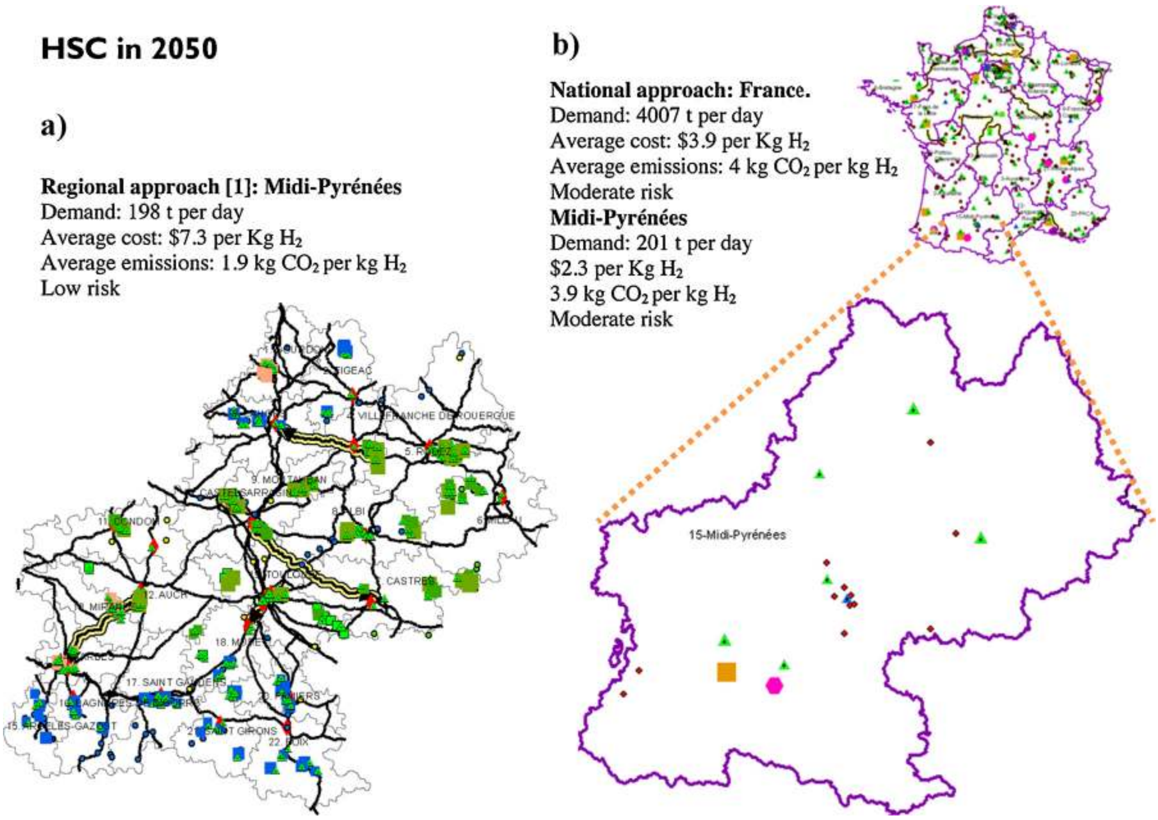

Fig. 8 – Midi-Pyrénées comparison as an independent optimised region or as an integrated region in a national approach.

By the other side, in both cases, the regions or districts tend to assume that each geographic area in the model follows exactly the same evolution in demand and energy source evolution. This is a questionable assumption, both because it ignores regional differences in economic and physical geography, and also because it ignores the infrastructure and marketing strategies already being developed by business, which focus planning on clusters around certain locations (Agnolucci and McDowall, May 2013).

The methodology proves its robustness to tackle different geographic scales but some differences between the regional and national cases were found especially due to the difficulty to find detailed input data related for both cases. The amount of energy sources for the Midi-Pyrénées region treated in the National case differs to the dedicated Midi-Pyrénées study (De-Leon, 2014). The order of magnitude about the availability for RES is different. We are aware that this difference could influence the results. No correction was yet performed in order to maintain the same orders of magnitude for all the regions. Finding uniform data for all regions is difficult but it remains an essential task.

7. Conclusions and perspectives

This study was devoted to strategic planning; an operational HSC design optimising three criteria (cost, environmental impact and safety risk). In this paper, the optimisation of the HSC was applied to the case of France. The objective was twofold: on the one hand, to examine if the methodology is robust enough to tackle a different geographic scale (comparing this case to a regional one) and second, to see if results are consistent between scales. To our knowledge, a few infrastructure optimisation studies tested the sensitivity of their analysis to assumptions about the geographic scale application of the model (to change from a regional to a national approach defining different breakdowns).

The same mathematical model used in De-Leon (2014) was applied for both regional and national cases but for the last one, new data collection, demand prediction and assumptions were involved. In this study, the ArcGIS® spatial tool was used before optimisation to identify the geographic items that were further used in the optimisation step as input in the MILP model. The multi-period problem was solved using multi-objective optimisation through ε-constraint method. Once the Pareto front was built, the M-TOPSIS method was adopted to find the best trade-off solution. After optimisation, the snapshot of the HSC was built by ArcGIS®.

In this study a homogenous demand calculation (taking into account the same % of market penetration for all regions or districts) has been treated but in reality, heterogeneity in data detail exists among locations, because of that a data reconciliation approach is highly recommended to deal with different geographic scales to reflect regional differences in economic and physical geography, and also the infrastructure and marketing strategies already being developed by business, which focus planning on clusters around certain locations as highlighted in Agnolucci and McDowall (May 2013). In this study, finding uniform data for all regions was difficult but it remains an essential task because of its influence on the final configuration as shown in the Midi-Pyrénées/France cases. Yet the demand transition rate in a long time planning horizon has an important effect on both, costs and technology choice as demonstrated in this study. In this work, the ArcGIS® analysis for both, pre- and post-optimisation stages was very useful to introduce real geographic constraints before optimisation and to validate the feasibility of results in the final HSC snapshot.

The differences between the cases support the importance to study different spatial scales which strongly influences the decision:

- the Midi-Pyrénées case (De-Leon, 2014) provides a more optimistic assessment of renewable energy sources (RES) based on electrolysis due to the detailed technical and locating data for RES sites and energy availability and tends to the decentralisation.
- the national case, offers the best option from the economic perspective. In this option, hydrogen is competitive since the first time period, producing H_2 from an energy mix led by biomass gasification. It is possible to identify potential subregions to produce and export hydrogen. A more detailed study to establish the intra-region flow rate remains necessary. The larger territory and demand, the geographic discretisation, the economies of scale and the consideration of initial storage and production plants have impacted the final results.

Finally, several perspectives can be suggested in order to improve the proposed framework.

- Demand modelling can be improved by the introduction of spatial variations in hydrogen demand.
- New energy sources (e.g. biogas) can be taken into account.
- The consideration of new technologies that currently are in development stage can be suggested: for instance carbon capture and storage, pipelines for high volume scenarios using the current natural gas pipeline to inject a H_2 percentage.
- The possibility to use the by-produced hydrogen integrating the additional costs associated to the purification step can be studied.
- Concerning optimisation, the use of dynamic programming (DP) can be a more appropriate way to model the problem.
- A rigorous treatment of uncertainty, going beyond the attempts we have seen so far in the literature, would be a very useful improvement for policy maker and private investors.
- Concerning the production cost in the mathematical model, the unit production cost (UPC) remains static for all the time periods. In the reality, the cost and availability of feedstock are critical and not fixed. The UPC can thus be changed considering: fixed facilities costs (maintenance, labour cost), electricity cost and feedstock cost with variations for each time period.

Appendix A.

A.1. *Supply chain decision database*

See Tables A1–A4.

Table A1 – Total demand for product form *i* in district *g* during time period *t* -D^T_{igt}- (kg per day).

kg per day in each time period				
Region/time	2020	2030	2040	2050
1	4653	34898	81430	116328
2	9091	68183	159093	227276
3	3682	27618	64441	92059
4	3934	29504	68842	98346
5	4483	33620	78448	112068
6	8823	66172	154402	220575
7	6805	51035	119081	170116
8	3791	28434	66345	94779
9	3192	23940	55860	79800
10	5130	38477	89779	128256
11	24,040	180303	420707	601010
12	7140	53548	124945	178493
13	2088	15660	36539	52199
14	6089	45670	106564	152234
15	8070	60528	141232	201759
16	9189	68919	160811	229730
17	9484	71128	165966	237094
18	5728	42958	100235	143193
19	4854	36409	84953	121362
20	13,108	98312	229394	327706
21	16,923	126925	296159	423085
Total	160,299	1202240	2805227	4007467

Table A2 – Average delivery distance between districts *g* and *g'* (km per trip).

Main city		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Strasbourg	**1**	0	1099	682	797	500	681	693	363	253	632	551	730	891	156	956	601	1003	534	872	820	490
Bordeaux	**2**	1099	0	536	686	603	505	410	807	750	851	595	562	220	1002	263	913	406	783	227	721	580
Clermont-ferrand	**3**	682	536	0	669	465	681	272	669	428	670	457	238	310	680	274	753	582	768	430	521	191
Caen	**4**	797	686	669	0	370	181	397	399	617	164	212	907	587	640	861	392	280	262	459	1066	860
Dijon	**5**	500	603	465	370	0	602	193	204	247	371	158	724	383	352	657	442	503	329	387	635	484
Rennes	**6**	681	505	681	181	602	0	409	554	849	345	319	919	398	761	672	573	99	443	278	1078	757
Orléans	**7**	693	410	272	397	193	409	0	397	440	398	185	510	190	545	464	486	310	356	194	793	677
Châlons-en-Champagne	**8**	363	807	669	399	204	554	397	0	377	400	187	928	587	207	861	238	549	171	591	944	614
Besançon	**9**	253	750	428	617	247	849	440	377	0	728	405	477	630	252	904	615	750	548	634	567	237
Rouen	**10**	632	851	670	164	371	345	398	400	728	0	213	908	588	607	862	228	444	98	623	1027	697
Paris	**11**	551	595	457	212	158	319	185	187	405	213	0	695	375	394	649	301	362	171	379	972	642
Montpellier	**12**	730	562	238	907	724	919	510	928	477	908	695	0	548	729	299	1166	820	866	789	159	240
Limoges	**13**	891	220	310	587	383	398	190	587	630	588	375	548	0	794	274	676	300	546	120	831	501
Metz	**14**	156	1002	680	640	352	761	545	207	252	607	394	729	794	0	954	445	756	378	739	819	489
Toulouse	**15**	956	263	274	861	657	672	464	861	904	862	649	299	274	954	0	1099	573	820	394	458	465
Lille	**16**	601	913	753	392	442	573	486	238	615	228	301	1166	676	445	1099	0	672	130	697	1182	852
Nantes	**17**	1003	406	582	280	503	99	310	549	750	444	362	820	300	756	573	672	0	533	179	979	773
Amiens	**18**	534	783	768	262	329	443	356	171	548	98	171	866	546	378	820	130	533	0	550	1115	785
Poitiers	**19**	872	227	430	459	387	278	194	591	634	623	379	789	120	739	394	697	179	550	0	951	621
Marseille	**20**	820	721	521	1066	635	1078	793	944	567	1027	972	159	831	819	458	1182	979	1115	951	0	330
Lyon	**21**	490	580	191	860	484	757	677	614	237	697	642	240	501	489	465	852	773	785	621	330	0

Table A3 – Road risk between grids *g* and *g'* (units).

Main city		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Strasbourg	**1**	0	7	4	9	3	13	9	4	3	8	8	13	9	3	11	7	10	5	10	8	7
Bordeaux	**2**	7	0	5	7	6	7	5	7	7	9	9	6	4	11	4	13	5	10	4	9	7
Clermont-ferrand	**3**	4	5	0	6	2	7	2	5	4	6	6	5	2	6	5	10	6	8	4	9	4
Caen	**4**	9	7	6	0	7	3	5	7	8	2	6	13	7	9	10	6	5	3	8	15	10
Dijon	**5**	3	6	2	7	0	11	5	2	2	6	5	7	5	4	6	6	7	3	5	9	4
Rennes	**6**	13	7	7	3	11	0	6	12	12	4	10	14	7	14	9	8	4	5	5	15	10
Orléans	**7**	9	5	2	5	5	6	0	6	6	3	5	10	3	8	6	8	5	6	3	10	8
Châlons-en-Champagne	**8**	4	7	5	7	2	12	6	0	3	6	5	9	7	3	9	5	9	2	6	8	5
Besançon	**9**	3	7	4	8	2	12	6	3	0	7	6	8	4	3	10	7	8	4	7	9	5
Rouen	**10**	8	9	6	2	6	4	3	6	7	0	5	11	4	5	7	5	4	2	7	13	9
Paris	**11**	8	9	6	6	5	10	5	5	6	5	0	13	6	7	9	7	8	4	6	12	8
Montpellier	**12**	13	6	5	13	7	14	10	9	8	11	13	0	8	13	4	17	9	14	7	5	8
Limoges	**13**	9	4	2	7	5	7	3	7	4	4	6	8	0	9	4	10	4	7	2	9	5
Metz	**14**	3	11	6	9	4	14	8	3	3	5	7	13	9	0	10	7	12	4	8	10	7
Toulouse	**15**	11	4	5	10	6	9	6	9	10	7	9	4	4	10	0	12	7	10	5	7	9
Lille	**16**	7	13	10	6	6	8	8	5	7	5	7	17	10	7	12	0	12	4	9	14	10
Nantes	**17**	10	5	6	5	7	4	5	9	8	4	8	9	4	12	7	12	0	5	3	12	9
Amiens	**18**	5	10	8	3	3	5	6	2	4	2	4	14	7	4	10	4	5	0	9	13	9
Poitiers	**19**	10	4	4	8	5	5	3	6	7	7	6	7	2	8	5	9	3	9	0	11	7
Marseilles	**20**	8	9	9	15	9	15	10	8	9	13	12	5	9	10	7	14	12	13	11	0	7
Lyon	**21**	7	7	4	10	4	10	8	5	5	9	8	8	5	7	9	10	9	9	7	7	0
Total		148	140	104	146	102	173	116	117	120	122	144	192	114	149	153	176	140	126	124	204	146

Table A4 – Weigh factor risk of population in each grid or district in the Midi-Pyrénées region -WFP_g- (calculated similarly to that of Kim et al., 2011).

No.	Region	Population	Type	Score
1	Alsace	1,845,687.00	Small	1
2	Aquitaine	3,232,352.00	Medium	2
3	Auvergne	1,347,387.00	Small	1
4	Basse-Normandie	1,473,494.00	Small	1
5	Bourgogne	1,642,115.00	Small	1
6	Bretagne	3,199,066.00	Medium	2
7	Centre	2,548,065.00	Medium	2
8	Champagne-Ardenne	1,335,923.00	Small	1
9	Franche-Comté	1,171,763.00	Small	1
10	Haute-Normandie	1,836,954.00	Small	1
11	Île-de-France	11,786,234.00	Large	3
12	Languedoc-Roussillon	2,636,350.00	Medium	2
13	Limousin	742,771.00	Small	1
14	Lorraine	2,350,920.00	Medium	2
15	Midi-Pyrénées	2,881,756.00	Medium	2
16	Nord - Pas-de-Calais	4,038,157.00	Large	3
17	Pays de la Loire	3,571,495.00	Medium	2
18	Picardie	1,914,844.00	Small	1
19	Poitou-Charentes	1,770,363.00	Small	1
20	Provence-Alpes-Côte d'Azur	4,899,155.00	Large	3
21	Rhône-Alpes	6,230,691.00	Large	3

Appendix B. Detailed results

See Tables B1–B3.

Table B1 – Results comparison in M-TOPSIS. France (2020–2050).

Altern.	Total daily cost ($ per day)	GWP (kg CO_2 per day)	Risk (units)	MATRIZ V [A*wj]			D+	D−	Ratio M-Topsis	Rank
x1	35331096.33	50049494.13	2410	0.145	0.124	0.038	0.232	0.084	0.267	6
x2	34097042.29	58049033.29	2405	0.139	0.144	0.038	0.227	0.102	0.311	8
x3	29287859.15	88658847.48	2405	0.120	0.220	0.038	0.222	0.175	0.441	19
x4	**37068448.13**	**34050415.79**	**3175**	**0.152**	**0.085**	**0.051**	**0.240**	**0.055**	**0.186**	**1**
x5	32016854.79	66048572.46	3175	0.131	0.164	0.051	0.214	0.121	0.361	12
x6	29508145.32	87941588.61	3175	0.121	0.218	0.051	0.211	0.174	0.452	21
x7	44665143.88	26050876.63	3782	0.183	0.065	0.060	0.236	0.073	0.236	3
x8	30571006.05	74048111.62	4600	0.125	0.184	0.073	0.194	0.144	0.425	17
x9	43992770.42	26050876.63	4769	0.180	0.065	0.076	0.226	0.077	0.254	4
x10	36216445.19	34050415.79	4797	0.148	0.085	0.076	0.223	0.064	0.222	2
x11	35301449.54	42049954.96	4795	0.144	0.104	0.076	0.213	0.076	0.264	5
x12	33628612.8	50049494.13	4791	0.138	0.124	0.076	0.206	0.091	0.306	7
x13	32845777.86	58049033.29	4798	0.134	0.144	0.076	0.199	0.108	0.352	10
x14	32008776.58	66048572.46	4700	0.131	0.164	0.075	0.195	0.126	0.392	14
x15	30707979.88	74048111.62	4760	0.126	0.184	0.076	0.192	0.144	0.429	18
x16	30087373.73	81999321.73	4783	0.123	0.204	0.076	0.190	0.163	0.463	23
x17	28631590.14	89485308.7	4799	0.117	0.222	0.076	0.192	0.181	0.485	27
x18	57364478.75	18051337.46	7901	0.235	0.045	0.126	0.205	0.148	0.418	16
x19	44033617.4	26050876.63	7907	0.180	0.065	0.126	0.197	0.111	0.360	11
x20	35704038.6	34050415.79	7994	0.146	0.085	0.127	0.194	0.102	0.345	9
x21	34179800.45	42049954.96	7900	0.140	0.104	0.126	0.184	0.109	0.371	13
x22	33090863.3	50049494.13	7900	0.135	0.124	0.126	0.174	0.120	0.407	15
x23	32286971.6	58049033.29	7900	0.132	0.144	0.126	0.166	0.133	0.446	20
x24	31119055.72	65910159.69	7900	0.127	0.164	0.126	0.161	0.148	0.480	25
x25	30391522.96	74048111.62	7900	0.124	0.184	0.126	0.156	0.164	0.513	29
x26	29391752.46	82023341.73	7900	0.120	0.204	0.126	0.156	0.181	0.538	31
x27	29074544.42	88501745.95	7900	0.119	0.220	0.126	0.155	0.196	0.557	36
x28	57412447.01	18051337.46	11000	0.235	0.045	0.175	0.186	0.181	0.494	28
x29	45645401.52	26050876.63	11020	0.187	0.065	0.176	0.174	0.156	0.472	24
x30	35901418.76	34050415.79	11002	0.147	0.085	0.175	0.174	0.146	0.457	22
x31	34584531.15	42049954.96	11000	0.141	0.104	0.175	0.161	0.152	0.485	26
x32	33253483.08	50049494.13	11000	0.136	0.124	0.175	0.151	0.160	0.514	30
x33	32306117.79	58049033.29	11001	0.132	0.144	0.175	0.141	0.170	0.546	34

Table B1 – (*Continued*)

Altern.	Total daily cost ($ per day)	GWP (kg CO_2 per day)	Risk (units)	MATRIZ V [A*wj]			D+	D−	Ratio M-Topsis	Rank
x34	31379205.49	66048572.46	11000	0.128	0.164	0.175	0.134	0.182	0.575	38
x35	30397115.1	74048111.62	11000	0.124	0.184	0.175	0.130	0.195	0.600	40
x36	29525747.51	82047650.79	11000	0.121	0.204	0.175	0.129	0.210	0.620	41
x37	28311473	90047189.96	11000	0.116	0.224	0.175	0.132	0.225	0.631	43
x38	57954947.47	18051337.46	14200	0.237	0.045	0.226	0.179	0.224	0.556	35
x39	44794626.85	26050876.63	14229	0.183	0.065	0.227	0.168	0.201	0.545	33
x40	36156572.94	34050415.79	14200	0.148	0.085	0.226	0.165	0.195	0.541	32
x41	34761377.23	42049954.96	14200	0.142	0.104	0.226	0.152	0.199	0.566	37
x42	33787340.33	50049494.13	14200	0.138	0.124	0.226	0.140	0.205	0.594	39
x43	32632169.27	58049033.29	14200	0.133	0.144	0.226	0.131	0.213	0.620	42
x44	31307709.47	66048572.46	14200	0.128	0.164	0.226	0.124	0.223	0.642	44
x45	30876060.69	74048111.62	14202	0.126	0.184	0.226	0.118	0.234	0.665	45
x46	29628363.27	82029177.07	14200	0.121	0.204	0.226	0.118	0.246	0.677	46

Table B2 – Summary of results for case France (2020–2050).

Variable	DLig (kg d^{-1})				Dlig (kg d^{-1})			
	2020	2030	2040	2050	2020	2030	2040	2050
G.1	4653	34898	10000	12440			71430	103888
G.2	9091	300	159093	227276		67883		
G.3	–	–	–	–	3682	27618	64441	92059
G.4	–	–	–	–	3934	29504	68842	98346
G.5	4483	1719	3565	9105		31901	74883	102964
G.6	8823	2716	154402	220575		63456		
G.7	6805	17528	119081	170116		33506		
G.8	3791	1888	4405	300		26546	61940	94479
G.9	3192	3161	3057	1500		20779	52803	78300
G.10	5130	10000	10000	10000		28477	79779	118256
G.11	400	180303	420707	601010	23640			
G.12	7140	1777	9963	10753		51771	114982	167740
G.13	2088	3311	300	3036		12349	36239	49164
G.14			106564	152234	6089	45670		
G.15	3210	60528	141232	201759	4860			
G.16	9189	15459	11122	15889		53460	149689	213841
G.17	9484	71128	165966	237094	–	–	–	–
G.18		42958	100235	143193	5728			
G.19	4854	300	4335	6574		36109	80618	114788
G.20	13108	62485	229394	327706		35827		
G.21	16923	126925	296159	423085	–	–	–	–

Table B3 – Flow rate of liquid hydrogen via tanker truck. France (2020–2050).

From region	To region	Flow rate, $Q_{ilgg'}$ (kg d^{-1})			
		2020	2030	2040	2050
1	14	6089			
2	13			36239	
2	19			5050	
6	4			68842	98346
7	3	3682		57314	92059
7	13				49164
7	19			24205	3500
8	11	5709			
10	4	3934			
10	11	14432			
10	18	5728			
11	5		28081	74883	102964
12	15	4860			
14	1			71430	103888
14	9			52803	78300
15	2		67883		
15	12		51771	59068	
15	13		12349		

Table B3 – (Continued)					
From region	To region	Flow rate, $Q_{ilgg'}$ (kg d^{-1})			
		2020	2030	2040	2050
15	19		3760		
15	20		4010		
16	11	3500			
17	6		63456		
17	7		33506		
17	19		32348	51364	111288
18	4		29504		
18	8		26546	61940	94479
18	10		28477	79779	118256
18	14		45670		
18	16		53460	149689	213841
20	12			55913	167740
21	3		27618	7127	
21	5		3820		
21	9		20779		
21	20		31818		

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