Hydrogen supply chain optimization for deployment scenarios in the Midi-Pyrénées region, France

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Several roadmaps and international projects are interested in the development of the hydrogen economy for the transportation system. Yet, the development of a hydrogen economy suffers from a lack of infrastructure to store and supply H_2 fuel to the refuelling stations, while at the same time, hydrogen can be just seen as one alternative among others to compete with the current fossil fuels. To determine if hydrogen is a competitive option, many scenarios must be assessed considering not only the cost as the target to determine the feasibility but, also environmental and safety objectives. This work is focused on the design of a hydrogen supply chain for deployment scenarios in the Midi-Pyrénées region in France based on multi-objective optimization. Specific constraints related to the energy sources have been integrated and a multi-period long-term problem is examined (2020–2050). Two solution strategies will be implemented to solve this multi-period problem: a global optimization through ε-constraint method and a sequential optimization through lexicographic and ε-constraint methods. The consideration of different geographical scales and the impact of the initiation step in the development of a sustainable supply chain have been highlighted.

Introduction

In the transportation sector, future technologies for internal combustion engine (ICE), hybrid electric cars such as plug-in hybrid electric vehicles (PHEV), battery electric cars (BEV) and fuel cell electric vehicles (FCEV) are being developed. The use of different fuels constitutes promising alternatives such as biodiesel, biomethane, bioethanol, liquefied petroleum gas and hydrogen (H_2). Hydrogen can be used in ICE vehicles (as liquid) or in FCEV in its gaseous form, thus reinforcing its interest as a promising energy carrier. The roadmaps for the development of a hydrogen economy are widely deployed by many countries around the world. Roadmaps have been generally used to aid decision-making and business planning. Some examples of roadmaps in Europe are the HyWays [1] project and H_2 Mobility [2], fixing a plan to introduce the use of FCEV in Europe, starting in Germany and UK whereas H_2 Mobility France began in 2013. In this program, the main car manufacturers and gas producers are involved. Private and public actors, in regional, national and international scales, coordinated by the French Association for Hydrogen and Fuel Cells [3] and under the aegis of the Ministry of Ecology, Sustainable Development and Energy will develop a roadmap with the basis of different deployment scenarios for FCEV and refuelling stations, showing the benefits and costs of the transition data. Transition plan scenarios can also be taken as an important basis for more precise studies where the different potential activities of the network can be measured and analysed. An example is the [4] study which provides a factual comparison of four different power-trains – BEVs, FCEVs, PHEVs and ICEs – on economics, sustainability and performance across the entire supply chain between now and 2050, based on confidential and proprietary industry data. These works can be considered as the starting point to launch more detailed analysis because of the definition of general targets and of the coordination and communication efforts from which valuable information is shared. The principal limitations related to these macro studies are yet the difficulty to generate specific results related to the location, size and number of production, storage or transport units and also the lack of interconnections between the different objectives.

A literature review shows that the most common approach in designing and modelling the so-called hydrogen supply chain (HSC) are the optimization methods through mathematical models. The aim of such methods is to find out optimal configurations according to some specific criteria (e.g. economic, safety, environmental aspects). One of the main advantages of this type of modelling is that mathematical models form a bridge to the use of high-powered mathematical techniques and computer to analyse the problems (Hillier and Lieberman, 2001).

This paper involves a mathematical approach to design the HSC for the Midi-Pyrénées region, which is the largest region of mainland France (similar to the surface of Denmark). This region is located in the South West corner of the country, next to Spain and counts with a large number of stakeholders and has great potential for producing hydrogen based on renewable sources which represented over than 25% in the region and 14% of national production in 2008 [5]. One of the main motivations of the region to evaluate the hydrogen economy is the reduction in green-house gas (GHG) emissions; the French Climate Plan has as targets to divide by 4 the French GHG emissions by 2050. In this context, the "Green H_2 fuel" project was launched to assess the sustainable development of the HSC. Multi-objective optimization will be applied for a regional problem considering four time periods with different solution strategies.

The remainder of this paper is organized as follows: in the next section, the literature review is presented. The specific context of the proposed work is described in Section Study context followed by the methodology and the problem definition. In Section Mathematical model, the extended version of the mathematical model presented in Ref. [6] is proposed. Section Solution strategy is dedicated to the solution strategies for the multi-objective and multi-period problem. Due to the multi-period formulation involving four time periods, two approaches are used to solve the problem: first, *case A* optimizes the four time periods in an integrated way, then, case B optimizes four mono-period problems sequentially. The optimization results and subsequent discussion for all cases are given in Section Results and discussion. Finally, conclusions and perspectives are given.

Literature review

The literature review shows that the most common approaches in designing and modelling the HSC are the optimization methods through mathematical models. Mixed Integer Linear Programming (MILP) approaches have been widely used. Almansoori et Shah [7], have clearly introduced a general model that determines the optimal design of a network (production, transportation and storage) for vehicle use where the network is demand-driven. The model was applied to a Great Britain case. Later, the same authors extended the model in 2009 [8], to consider the availability of energy sources and their logistics, as well as the variation of hydrogen demand over a long-term planning horizon. Other works [9] take into account demand uncertainty arising from long-term variation in hydrogen demand using a scenario-based approach. Demand uncertainty for HSC is also studied in Refs. [10,11]. Murthy Konda et al. [12] considered the technological diversity of the H_2 supply pathways together with the spatial-temporal characteristics to optimize a large-scale HSC in Netherlands minimizing a cost objective based on Refs. [7,8] approaches.

Multi-objective optimization for cost and environmental criteria has been treated by Hugo et al. [13] who investigates different hydrogen pathways in Germany. Other cases of this bi-criteria optimization are [14] for a Great Britain case and [15] for Spain.

Kim and Moon [16,17] developed expressions to evaluate the total risk of production and storage facilities as well as the total transport risk where the relative risk of hydrogen activities is determined by risk ratings calculated based on a risk index method. Ref. [18] describes the risk hazards (delimitation and explanation of potential risks in some parts of the hydrogen infrastructure: pipeline and storage tank) to demonstrate the consequence of hydrogen accident in case of a future infrastructure operation. The abovementioned works are based on the study of Rosyid et al. [19].

These works are limited to a bi-criteria assessment, generally based either on cost-environment or on cost-safety. They have being applied mostly to a country scale with consideration of a mono or multi-period problem. A multi-objective problem was treated by Ref. [6] where three criteria were examined: cost, environmental impact and safety risk. This approach will be extended in the present work.

In a recent work [20], the spatial scales for HSC studies has been examined (e.g. from national to local) and they conclude that hydrogen demand assumptions have been neglected in the literature and do not consider the regional particularities. One of the main questions arising from the regional French case treated here is whether or not the geographic segmentation that was adopted, i.e., the regional scale is consistent to ensure a competitive cost. From an economic viewpoint, an average cost of hydrogen of US$ 4.74 per kg H_2 (3.6 €/kg) could be considered as acceptable by 2050 if not subject to excessive taxes [1]. It is important to study this regional scale and then to check its consistency towards the national case. To our knowledge and as reported in Ref. [20], a few infrastructure optimization studies tested the sensitivity of their analysis to assumptions about the spatial and temporal dynamics of demand.

Then, the originality of this study is to take into account a three-objective problem (economic, environmental and safety criteria are optimized at the same time) in a multi-period framework (2020–2050) applied across a range of spatial scales (in this work only the regional case is explained). Due to the problem size, two strategies are proposed to solve the problem: first, a general multi-objective problem is solved (i.e. the four-time periods are integrated) and the solution is based on the so-called ε-constraint methodology. In a second time, a sequential optimization is carried to solve four mono-period problems with the lexicographic optimization and then ε-constraint methodology and TOPSIS to each time period.

Study context

The "Green H_2 fuel" project (*Hydrogène vert carburant*) was initiated by the PHyRENEES[1] association, the Regional Innovation Agency (Midi-Pyrénées Innovation-MPI)[2] and the Chemical Engineering Laboratory (Laboratoire de Génie Chimique-LGC) on February 2012. This study emerged as an initiative to evaluate the hydrogen economy in the Midi-Pyrénées region to enhance renewable energies and at the same time to evaluate the potential CO_2 reductions. More specifically, the objectives of the project are based on the following items:

- identification of the key stakeholders in Midi-Pyrénées
- scenarios definition
- data collection and assumptions
- model adaptation, optimization and validation
- results analysis

The methodological framework of the study is proposed in Fig. 1. The *input* block corresponds to all the databases, hypothesis and scenarios chosen by the steering committee. The integration of the mathematical model and the multi-objective optimization approach constitute the core of the approach. The snapshots and the results concerning the decision variables and objective functions are the main *outputs*.

Methodology

Problem definition

The optimization approach of HSC proposed by Refs. [6,21], has been adapted to the Midi-Pyrénées region to answer the following questions:

- what is the best option for production and storage of hydrogen in Midi-Pyrénées?
- is centralized production or decentralized production (small-scale production at local fuelling) more cost effective?
- what are the most cost effective transportation modes and pathways to connect hydrogen demand with its supply?
- is it possible to find competitive targets for a regional-scale?
- does the well-to-well (WtW) assessment of the HSC result in less CO_2 emission than those related to gasoline and diesel?
- what is the safest configuration of the HSC in Midi-Pyrénées?

Objective

This work focuses on the design of an HSC for the Midi-Pyrénées region in five levels: energy sources, production, storage, transport and market (Fig. 2). There are three objectives to be minimized: the cost, the environment impact expressed in terms of GWP (CO_2 emissions) and the safety risk. Finally, four time periods are considered (2020–2050) with a time step of 10 years.

Data collection

The territory breakdown has considered districts instead of grids and a deterministic demand for each district is assumed. The data set includes information relating to the hydrogen demand, technical, environmental, economic and risk data associated with each component of the HSC. Some values have been collected from recent publications (ADEME, INSEE, CNRS, etc.), visits to sites, and interviews with professionals in the energy region and professors (sociologists and researchers specialized in the energy field).

Techno-economic data

A large amount of input data is required to solve the problem. All the techno-economic parameters (i.e., minimum and maximum production and storage capacities, average delivery distance between grids and capacity of each transportation mode, etc.) are defined in Appendix A. In this section we present only the main specific issues linked to the Midi-Pyrénées region.

The geographic breakdown

According to its geographic and administrative segmentation, Midi-Pyrénées is divided into districts: this represents 22 zones (see Fig. 3). This division has been used to obtain a realistic path between districts with the existence of major roads and to estimate the potential demand from regional statistics from the National Institute of Statistics and Economic Studies (INSEE).

Energy sources and production facilities

The availability of renewable energy sources used for this study was gathered from Ref. [22]. Fig. A1 in the Appendix A takes into account the large renewable energy sources (RES) sites for wind power with a capacity higher than 0.5 MW, for

[1] PHyRENEES Association was established in October 2007 around several partners (Ecole des Mines, Trifyl, N-GHY, Airbus, GDF INPT, ARAMIP and the General Council of the Tarn…).

[2] MPI was created in 2006 at the initiative of the Regional Council to improve the visibility of the institutional landscape and guide companies in their innovation projects.

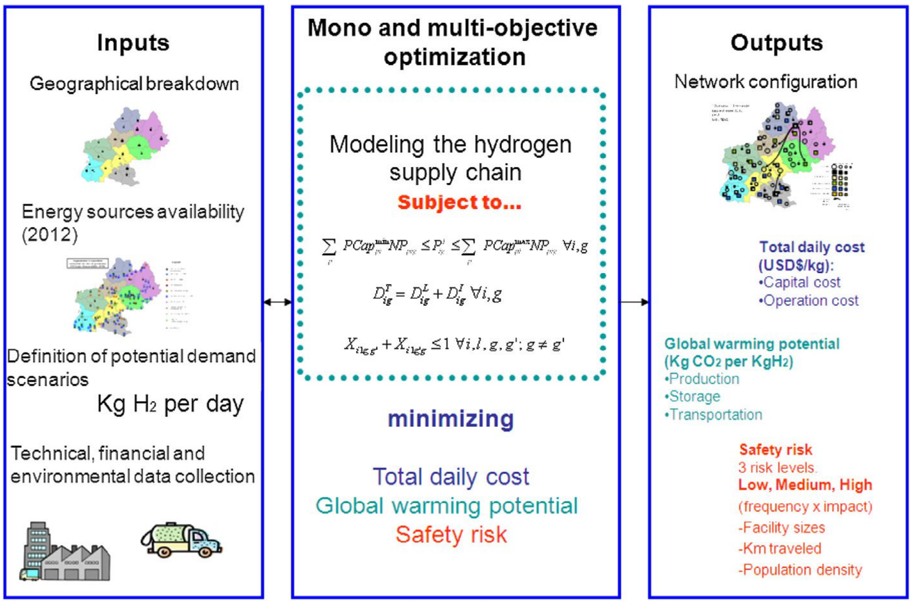

Fig. 1 – Methodology framework for the "Green H_2 fuel" project (Midi-Pyrénées).

PV more than 1 MWp and hydropower of more than 0.5 MW. The data was in agreement with the study of the Regional Climate Air Energy forecasting for Midi-Pyrénées [5] approved in June 2012 by the region. This report presents the strategic objectives for the development of renewable energy in 2020. The zones with potential development of RES are presented in Fig. A2 in the Appendix A. Based on this study and considering the current energy situation, the initial average availability of primary energy source e in grid g during time period t (kWh per day) from 2020 to 2050 is presented in the Appendix A.13. For hydropower, only facilities "run-of-river" are considered (based on data collection from EDF), which represent 28.6% of the total hydropower in the region against 71.4% for the "pumped-storage hydroelectricity" facilities. Because of the potential of renewable energy (wind, solar and hydro) in the region, production of hydrogen by electrolysis of water was selected. The potential use of nuclear electricity is also considered. However, the commercial production technology used today is mainly based on steam methane reforming: the comparison of this method with those using renewable sources appears relevant. A large difference in the proportion of energy sources is highlighted in 2012, 2020 and 2030 (e.g. hydro ratio is 78% in 2012, 48% in 2020 and 39% in 2030); this change is due to the projections of the Regional Climate Air Energy forecasting for Midi-Pyrénées. For 2040–50 no projection was found and an assumption of a 2% increase in the total

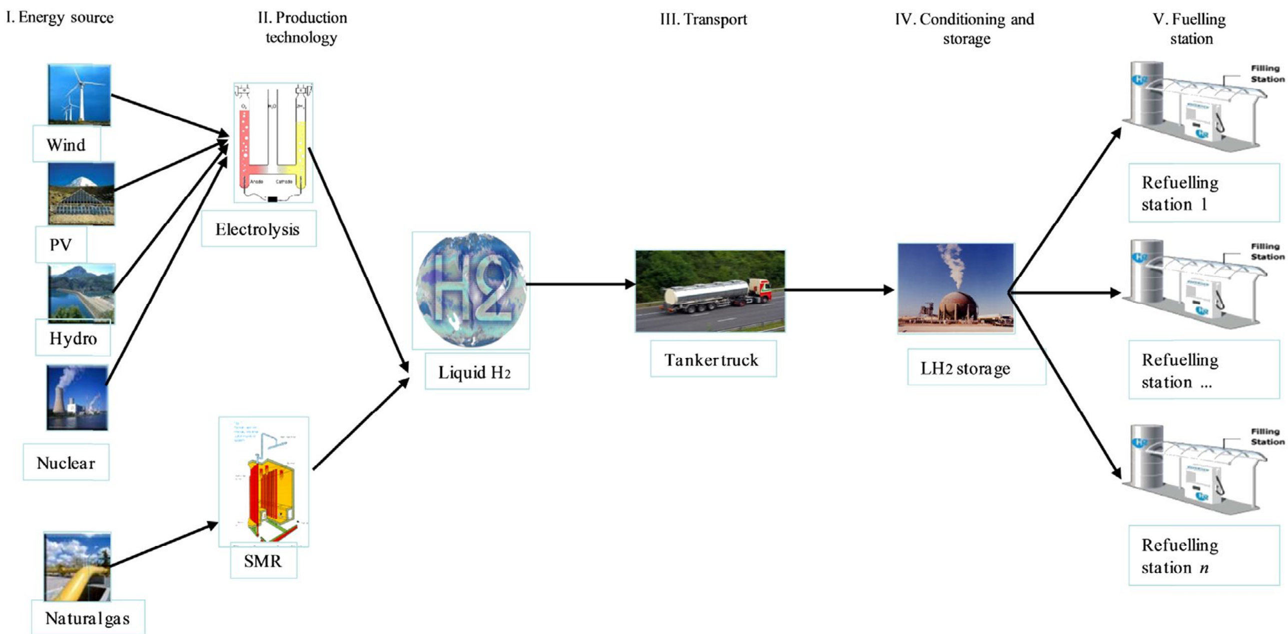

Fig. 2 – The hydrogen supply chain studied for the Midi-Pyrénées region.

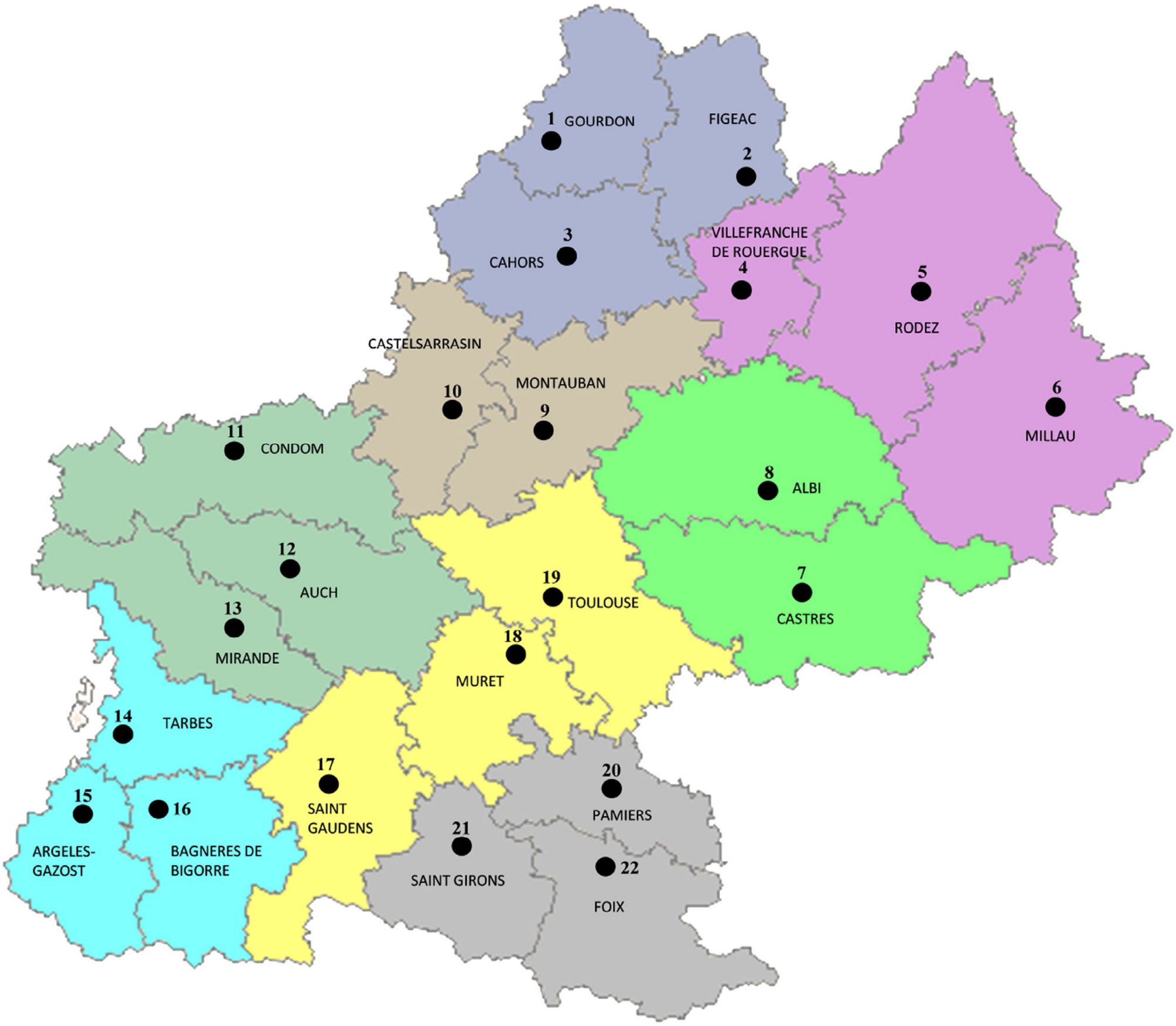

Fig. 3 – Geographic breakdown in districts for the Midi-Pyrénées region.

energy production capacity was adopted (this percentage per type of RES remains the same).

Conditioning, storage and transportation

This study focuses only on the conditioning, storage and distribution of liquid hydrogen (LH_2) that is considered instead of compressed gaseous hydrogen (CH_2) because it has several advantages over gas. LH_2 has a very high energy density, it is easier to handle, transport and store [8]. From the economic point of view, transportation of LH_2 is cheaper than from a gas network, as highlighted by Ref. [7]. Storage could be performed in liquid phase with stainless steel tanks (cryostats) by the Claude cycle which lowers the temperature to −253 °C (liquefaction temperature) [23] with a density of 70.85 kg/m^3 vs. 0.0899 kg/m^3 for the CH_2.

Refuelling stations

The final step is the refuelling station for the vehicles supply. The model only computes the number of fuelling stations to be installed. Ref. [4] considered 3 types of refuelling stations where H_2 is considered as liquid at 30 bar pressure or gaseous at 250 or 450 bar. Then, H_2 is compressed to 350 or 700 bar; for this case, only one size of refuelling station with 10 dispensers to provide maximum 2.5 t H_2 per day is considered.

Demand estimation

A deterministic demand of hydrogen for FCEV is considered, including fleets such as buses, private and light-good-vehicles and forklifts at 2010 levels. Market demand scenarios selected for this study were based on two studies: Refs. [4,24]. From these studies and the involved assumptions, two scenarios concerning two levels of demand for fuel cell electric vehicles penetration were developed (see Table 1). The scenario S1 refers to a low demand scenario and the S2 is an optimistic one.

The potential demand for hydrogen in these two scenarios is computed according to Eq. (1) as in the works of Refs. [7,12].

$$D_{ig}^{T} = \mathrm{FE} \cdot d \cdot Qc_g \quad (1)$$

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 Appendix A.1,2).

Assumptions

The study is based on the following assumptions:

- a capital change factor of 12 years is introduced;
- several sizes and types of production units and storage facilities are considered; a minimum capacity of production and storage equal to 50 kg of H_2 per day is taken into account;
- renewable energy is directly used on-site because of grid saturation. This allows to allocate the CO_2 impact to each source;
- inter-district transport is allowed, intra-district distribution is not taken into account;
- the maximum capacity of LH_2 transportation is fixed at 3500 kg [25];
- a 10-days LH_2 safety stock is considered;
- the risk index is calculated by the methodology proposed in Refs. [16,17];
- a 2% RES increase in each period from 2030 to 2050;
- the number of plants is initialized at a null value: the H_2 plants that exist are supposed to provide exclusively the demand for chemical industry requirements (i.e., an SMR plant in Boussens);
- the cost of migrating a current refuelling station to H_2 fuel is not considered;
- the learning rate cost reductions due the accumulated experience is considered as 2% per period (McKinsey & Company, 2010);
- only the "low demand" scenario is solved.

Mathematical model

In the proposed formulation, the hydrogen can be produced from an energy source e, delivered in a specific physical form i, such as liquid, produced in a factory type involving different production technologies p, stored in a storage unit s and distributed by a transportation mode l from one district g to another g' (with $g' \neq g$) (see Fig. 2).

To model the HSC for the region, constraints used are similar to those of (Almansoori and Shah, 2009) and De-León Almaraz et al. [6]. The model remains as mixed integer linear programming (MILP). However, for the Midi-Pyrénées case study, a multi-period optimization approach was carried out with the objective of minimizing the criteria on the entire time horizon t. Another specific feature for this case is the integration of renewable energy constraints. The indices t (time period) and j (facility size) are added to all the constraints of the model presented [6], in this section only the new constraints are presented.

Table 1 – Demand scenarios of fuel cell electric vehicles penetration by period.

Scenario/year	2020	2030	2040	2050
S1: scenario 1 (buses, private and light-good-vehicles)	1%	7.50%	17.50%	25%
S2: scenario 2 (buses, private and light-good-vehicles)	2%	15%	35%	50%
S1/S2: scenarios 1 and 2 (forklifts)	4%	30%	70%	100%
Total S1 (t H_2 per day)	7.9	59.4	138.7	198.1
Total S2 (t H_2 per day)	15.5	116.9	272.8	389.8

Energy source constraint

The average availability of primary energy sources e in a grid g during time period t is given as a sum of three terms. These are the initial average availability of primary energy sources, the import of primary energy sources and the rate of consumption of these sources. γ_{epj} is the rate of utilization of primary energy source e by plant type p and size j and is multiplied by the safety stock factor (SSF = 5%) for storing a small inventory of primary energy sources. The terms are expressed respectively by the following constraint:

$$A_{egt} = A0_{egt} + IPES_{egt} - SSF \sum_{pji} \gamma_{epj} PR_{pijgt} \quad \forall e, t, g; g \neq g\prime \tag{2}$$

Production facilities constraints

The number of production facilities type p and size j installed in g in the first time period NP_{pijgt1} is determined by the sum of the total initial number of production facilities ($N0_{pjjg}$), and the number of new plants of type p producing product form i in grid g in the period one (IP_{pijg1}):

$$NP_{pijgt_1} = NP0_{pjig} + IP_{pjigt_1} \quad \forall p, i, j, g, t = 1 \tag{3}$$

For all the other periods, the definition of the number of new production facilities takes into account the production plants established in the previous time period.

$$NP_{pijgt} = NP_{pjigt-1} + IP_{pjigt} \quad \forall p, i, j, g, t \neq 1 \tag{4}$$

In the case of new electrolysis plants that use renewable energy ($IP_{electrolysis\text{-}RES,i,j,g,t}$) they can be established only when renewable energy e is available in the grid g. For the Midi-Pyrénées region, exportation of renewable energy between grids g to g' is not considered due to network saturation, then, if the initial availability of renewable energy source $A0_{egt}$ in g is zero, non-electrolysis plants can be installed in this district g.

$$IP_{electrolysis(RES)ijgt} = 0 \;\; if \;\; A0_{e(RES)gt} = 0 \quad \forall g \tag{5}$$

The number of storage units (NS_{sijgt}) is determined by the sum of the total initial number of storage facilities of type s and size j storing product form i in grid g established in the previous time period t-1($NS0_{sjig}$ or $NS_{sigt\text{-}1}$) and the number of new storage units of type s producing product form i in grid g during the time period t (IS_{sigt}):

$$NS_{sijgt_1} = NS0_{sjig} + IS_{sijgt_1} \quad \forall s, i, j, g, t : 1 \tag{6}$$

$$NS_{sijgt} = NS_{sjigt-1} + IS_{sijgt} \quad \forall s, i, j, g, t \neq 1 \tag{7}$$

Refuelling stations

The number of refuelling stations within a grid g dispensing a product form i depends on the total equivalent demand and the installed capacity of the fuelling stations, as follows:

$$NFS_t = \sum_{i,g} \frac{D^T_{igt}}{FCap_i} \forall t \tag{8}$$

Total daily cost (economic objective)

For the treatment of the multi-period problem and with the addition of energy sources and refuelling stations constraints, some modifications must be addressed to the economic objective function. These changes are explained below:

Facility capital cost
The facility capital cost is calculated by multiplying the number of new plants and new storage facilities by their capital cost and the learning rate as the cost reductions when technology manufacturers accumulate experience during time period t.

$$FCC_t = \sum_{i,g} \frac{1}{LR_t} \left(\sum_{p,j} PCC_{pij} IP_{pjigt} + \sum_{s,j} SCC_{sij} IS_{sijgt} \forall t \right) \tag{9}$$

Primary energy sources transportation cost
The cost of transportation of primary energy sources for all scenarios during the entire planning horizon is equal to:

$$ESC_t = \sum_{e,g} UIC_e IPES_{egt} \forall t \tag{10}$$

Economic objective function
By combining the cost terms derived from the capital and operational facilities and transportation units, and results from equation (10), the total daily cost (TDC) of the hydrogen supply chain is defined as:

$$TDC = \sum_{t} \frac{FCC_t + TCC_t}{\alpha CCF} + FOC_t + TOC_t + ESC_t \tag{11}$$

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 (CCF) to find the cost per day in US dollars. This result is added to the facility and transportation operating (FOC_t, TOC_t) costs and to the cost of transportation of the energy source ESC_t.

Multi-objective optimization

The equations presented in a previous work [6] have been extended to optimize the total daily cost as well as the total relative risk (where the relative risk of hydrogen activities is determined by risk ratings calculated based on a risk index method) and global warming potential (GWPTot, in g CO_2-eq per day) at the same time. The global model can be formulated in a more concise manner as follows:

Minimize {TDC}

Subject to:

$h(x,y) = 0$

$g(x,y) \leq 0$

$x \in R^n,\ y \in Y = \{0,1\},\ z \in Z^+$

$Risk \leq \varepsilon_n \ (n = 0,1,2,\ldots,N)$

$TotalGWP \leq \varepsilon_m \ (m = 0,1,2,\ldots,M)$

{ Demand satisfaction; Overall mass balance; Capacity limitations; Distribution network design; Site allocation; Non-negativity constraints }

The objective of this formulation is to find values of the operational $x \epsilon R$, and strategic $y \epsilon Y = \{0,1\}$, $z \epsilon Z+$ decision variables, subject to the set of equality $h(x,y) = 0$ and inequality constraints $g(x,y) \leq 0$. In this model, the continuous operational variables concern decisions dedicated to sources, production, storage and transportation rates, 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 are expresses as linear functions of the associated decision variables levels. The solution consists of a Pareto front composed of solutions that represent different possibilities of supply chain configurations. To deal with the multi-period problem, two solution strategies are proposed in the next section.

Solution strategy

This problem is treated in GAMS 23.9 and solved by CPLEX 12. Two main cases are analysed here related to general and sequential multi-objective optimization approaches respectively.

Case A. General multi-objective optimization based on ε-constraint method

In this case, the problem is treated as a multi-period one. The tri-objective optimization problem is solved by implementing the ε-constraint method. In the ε-constraint method, introduced by Ref. [26] all but one objective are converted into constraints by setting an upper or lower bound (nadir and utopia points) to each of them, and only one objective is to be optimized [27]. By varying the numerical values of the upper bounds, a Pareto front can be obtained. The problem is now to select the best choice among these compromise solutions. This can be performed by use of a multi-criteria decision making methods. Ren et al. [28] presented the M-TOPSIS (Modified Technique for Order Preference by Similarly to Ideal Solution) method to evaluate the quality of the alternative and to deal the rank reversal problem.

Case B. Sequential multi-objective optimization based on lexicographic and ε-constraint methods

The hybrid strategy coupling lexicographic and ε-constraint method was also used in Ref. [6] for a mono-period problem.

At preliminary step, some efforts were devoted to solve the Midi-Pyrénées case as a multi-period to construct the pay-off table through lexicographic optimization but the multi-period problem turns out to be a difficult problem due to the problem size and the use of binary variables so that a feasible solution was not obtained. In order to overcome this limitation, the problem is treated here as four mono-period problems.

The time period t1 is optimized for the 3 objectives through lexicographic optimization to build the pay-off allows the application of the ε-constraint method. Lexicographic problems arise naturally when conflicting objectives exist in a decision problem but for reasons outside the control of the decision maker the objectives have to be considered in a hierarchical manner [29]. This method can be viewed as an "a priori" approach with aggregation using constraints in a decoupled method. In the lexicographic ordering, the objectives are ranked according to the order of importance.

Again, the M-TOPSIS analysis is carried out for each Pareto front with the same weighting factor for cost, safety and environmental criteria. The optimized network configuration then serves as initializing existing network for the period $t+1$ and the same procedure is applied until the four time periods are solved.

Results and discussion

Case A

The best and worst values for each criterion obtained from the results of *case A* lead to the nadir and utopia points for the whole time horizon: 25 ε-points were defined; the lower and upper bounds for the GWP correspond to the total GWP divided by the total demand, resulted in 1.94 and 10.7 kg CO_2-equiv per kg H_2 (in the mono-objective optimization reported in Ref. [30]). Similarly, lower and higher risk bounds were established. The ε-constraint methodology was applied adding inequality constraints related to the GWP and the risk values in the mathematical model and then optimizing the TDC. The multi-period approach was applied.

The solution consists of a Pareto front composed of 22 feasible solutions for supply chain configurations (Fig. 4). The best solution (see Appendix C.1) corresponds to the option with the average cost of $7.81 per kg H_2, GWP of 1.94 kg CO_2 per kg H_2 (average values are obtained dividing the TDC and the total GWP by the total demand for the 4 time periods) and a total risk of 406 units. The detailed configurations in each time period are presented in Fig. 5 and decision/operating variables are displayed in Table 2.

Renewable energy is used to produce hydrogen from 2020. The cost is yet extremely high ($23.4 per kg H_2) with a huge benefice in environmental impact. The risk of this configuration remains low for all the time periods because of the low level of transportation. Electrolysis is the main production technology using mainly wind power especially from 2030 to 2050.

The change from a centralized to a decentralized supply chain is the main difference observed when the three criteria are taken into account in the optimization phase compared to the cost minimal network presented in Ref. [30]. The production and storage sizes are mainly small-distributed units. Exported demand represents 6% in 2030 and 20% in 2050. Hydrogen is transported from districts 4, 12 and 19. The cost of the multi-objective approach is close to the targets set by the HyWays roadmap [1] by 2050 in the range $4.74–$7.11 per kg H_2. In the optimization, the obtained costs per kg H_2 are $7.2 and 6.7 for 2040 and 2050 respectively.

The main problem that can be found in this approach is that the integration of the four time periods leads to a high cost value in 2020 that may be viewed as prohibitive and thus may hinder the development of hydrogen deployment in the region. For this reason, another strategy was adopted assessing the whole problem as a mono-period problem in order to find if more competitive results can be reached.

Case B

An alternative to solve the multi-objective problem involves the lexicographic optimization to build the pay-off table (see Table 3) of only non-dominated solutions minimizing one

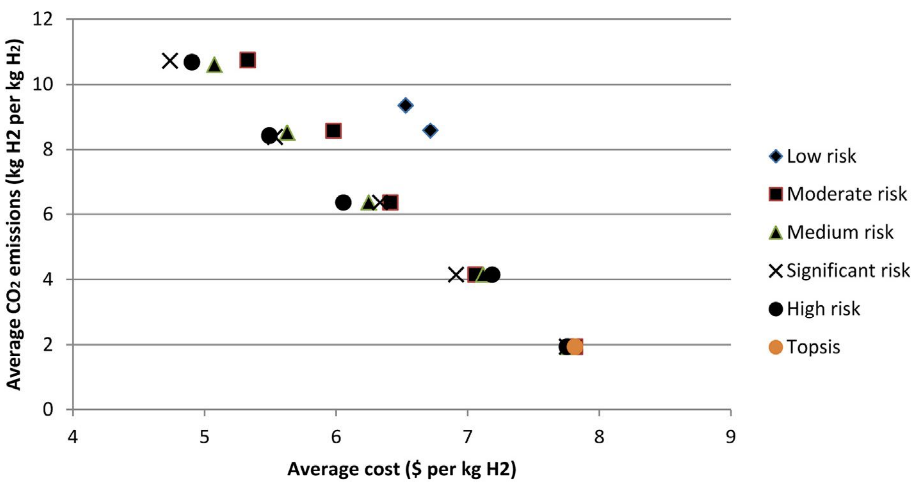

Fig. 4 – Pareto solutions for the multi-objective model for *case A*.

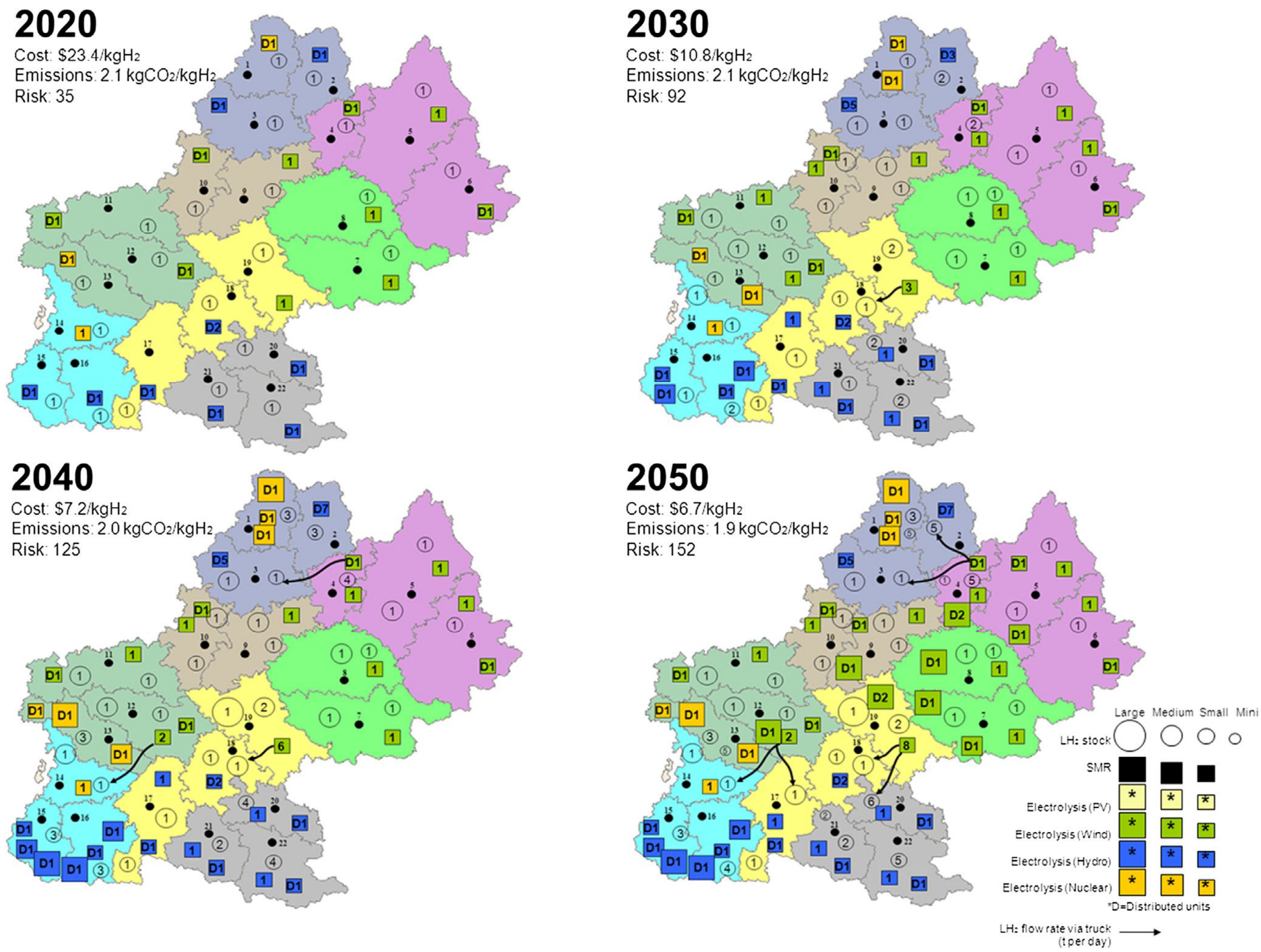

Fig. 5 – Network structure of liquid hydrogen distributed via tanker trucks. *Case A*: multi-objective optimization through ε-constraint method in a low demand scenario in the Midi-Pyrénées region.

objective function but also to find the best values for the two other criteria. The lexicographic optimization was tried to be applied for the multi-period problem but the large problem size involving especially a high number of binary variables was computationally prohibitive and no feasible solution was obtained after 48 h with GAMS version 23.9. Then, the multi-period approach is treated as four mono-period problems in a sequential way.

In the lexicographic optimization, the first time period (2020) was treated for the three objective functions. The pay-off table was built and ε-constraint method was applied with 3 risk levels and 10 GWP points. The Pareto fronts are proposed in Fig. 6 for the 2020, 2030, 2040 and 2050 periods. The M-TOPSIS analysis was then carried out and the top option was selected (see Appendix C.2). The decision variables are inserted as the initial number of production/storage facilities of type *s* and size *j* storing product form *i* in grid *g* in period *t*. Then, it is possible to optimize the next period time and so on until 2050.

Table 4 displays that the cost of $13.9 per kg H_2 in 2020 in the lexicographic optimization is lower than the value obtained in *case A* with a significant cost reduction of 41% (see Table 5): this is the main advantage of the solve strategy of *case B* because this cost reduction in the introduction phase of the H_2 fuel can be viewed as a limiting factor.

The list of the decision variables is presented in Table 4 and the network structure of liquid hydrogen distributed via tanker trucks for *case B* is shown in Fig. 7. Electrolysis is the main production technology. In 2050, 82% of H_2 is produced from wind, 15% from hydro and 3% from nuclear power. In the same year, 12% of the total demand is exported (district 18 is the main importer).

Similar values for the GWP criterion are found for *cases A* and *B*; this represents a benefit in cost compared to the simple cost optimization. Higher values for the relative risk index are obtained in *case B* because more production and storage units are established; the functions of relative risk are directly related to the number of these units. The partial vision regarding the demand only for one period promotes the design of small units only to be used in the defined time period instead of designing larger production plants to cover demand increments.

Yet, the flexibility of this method is that each period can be analysed in detail and that some parameters can be changed

Table 2 – Multi-objective optimization results of the hydrogen supply chain for case A.

Year	2020	2030	2040	2050
Demand (kg per day)	7898	59,430	138,790	198,170
Number of production facilities	23	44	56	70
Number of storage facilities	22	40	55	75
Number of transport units		1	3	6
Capital cost				
Plants and storage facilities (10^3 $)	5,724,485	1,161,990.3	512,401.5	335,000.9
Transportation modes (10^3 $)	0	500	1500	3000
Operating cost				
Plants and storage facilities (10^3 $ per day)	53.7	375.9	867.9	1239.6
Transportation modes (10^3 $ per day)	0	0.1	0.7	1.6
Total operating cost (10^3 $ per day)	53.7	376.0	868.6	1241.1
Total cost				
Total network cost (10^3 $ per day)	184.6	643.0	995.3	1333.7
Cost per kg H_2 ($)	23.4	10.8	7.2	6.7
Production facilities (10^3 t CO_2-equiv per day)	11.3	81.3	172.0	231.9
Storage facilities (10^3 t CO_2-equiv per day)	5.6	41.8	97.7	139.5
Transportation modes (10^3 t CO_2-equiv per day)	0	0.1	1.3	3.1
Total GWP (10^3 t CO_2-equiv per day)	16.9	123.2	271.0	374.4
Kg CO_2-equiv per kg H_2	2.1	2.1	2.0	1.9
Production facilities risk	6	12	17	25
Storage facilities risk	29	73	95	105
Transportation modes risk	0	7	13	24
Total risk (Units-level)	35	92	125	154

to reflect the preferences of the decision maker. Finally, the necessity to run each optimization separately and to capture the decision variables (production plants, storage facilities and number of transportation units) to optimize the next period could represent a risk in data capture and processing.

Cases comparison

In Table 5, all results between mono- and multi-objective cases are listed. The bold characters in the table are relative to the value of the optimized criterion for the mono-objective optimization and in the case of the lexicographic optimization are related to the first optimized objective (higher priority).

If *cases A* and *B* are compared, *case B* is better in 2020 and 2030 with a cost reduction of 41% and 16% respectively, while no variation in CO_2 is observed but the associated risk increases due to the presence of more production and storage units that are installed in the region. The highest impact for the risk lies in 2040 and 2050.

Table 5 shows that the best value obtained for cost in the multi-objective approach (*case A*) is higher than for mono-objective case minimizing TDC (an increase by 80% is observed by 2040–50). Besides, the unitary cost in 2020 is higher by 44%, which is a non-competitive cost of $23.4 per kg H_2. The associated risk for this network is 42% lower by 2050. Besides, it was found that the GWP decreases by 70–80% comparing multi-objective vs. the TDC minimization and the risk minimization because of the production mix.

It must be highlighted that similar trends are observed for GWP between the GWP minimization and *case A* but a benefice in cost resulted in *A* since hydrogen is cheaper in 2030 (23%) and 2050 (27%). The use of renewable energy has a ratio of 92% in 2020, wind power is the predominant energy source followed by hydropower. Nuclear energy starts with a rate of 8% in 2020 but decreases to 3% by 2050. A moderate risk can be observed due to the lack of transportation.

In 2050, three scenarios are under the maximal target of the HyWays roadmap concerning cost: the cost and risk minimization cases and the multi-objective *case A*, however *case B* is very close to the bound (see Fig. 8).

The M-TOPSIS ranking leads to a significant decrease in CO_2 emission for *cases A* and *B*, for example, the gain is of a

Table 3 – Pay-off table obtained by the lexicographic optimization.

Minimize	2020			2030			2040			2050		
	TDC	GWP	Risk	TDC	GWP	Risk	TDC	GWP	Risk	TDC	GWP	Risk
Cost per kg H_2 ($)	**13.4**	15.6	14.7	**7.8**	10.1	8.4	**5.7**	9.1	8.4	**5.0**	8.0	6.7
Kg CO_2-equiv per kg H_2	5.1	**2.1**	5.6	8.7	**2.1**	9.5	9.4	**2.0**	6.5	9.1	**2.0**	5.8
Total Risk (Units-level)	42	34	**34**	117	92	**91**	258	177	**167**	372	259	**246**

Bold characters are related to the first optimized objective (higher priority).

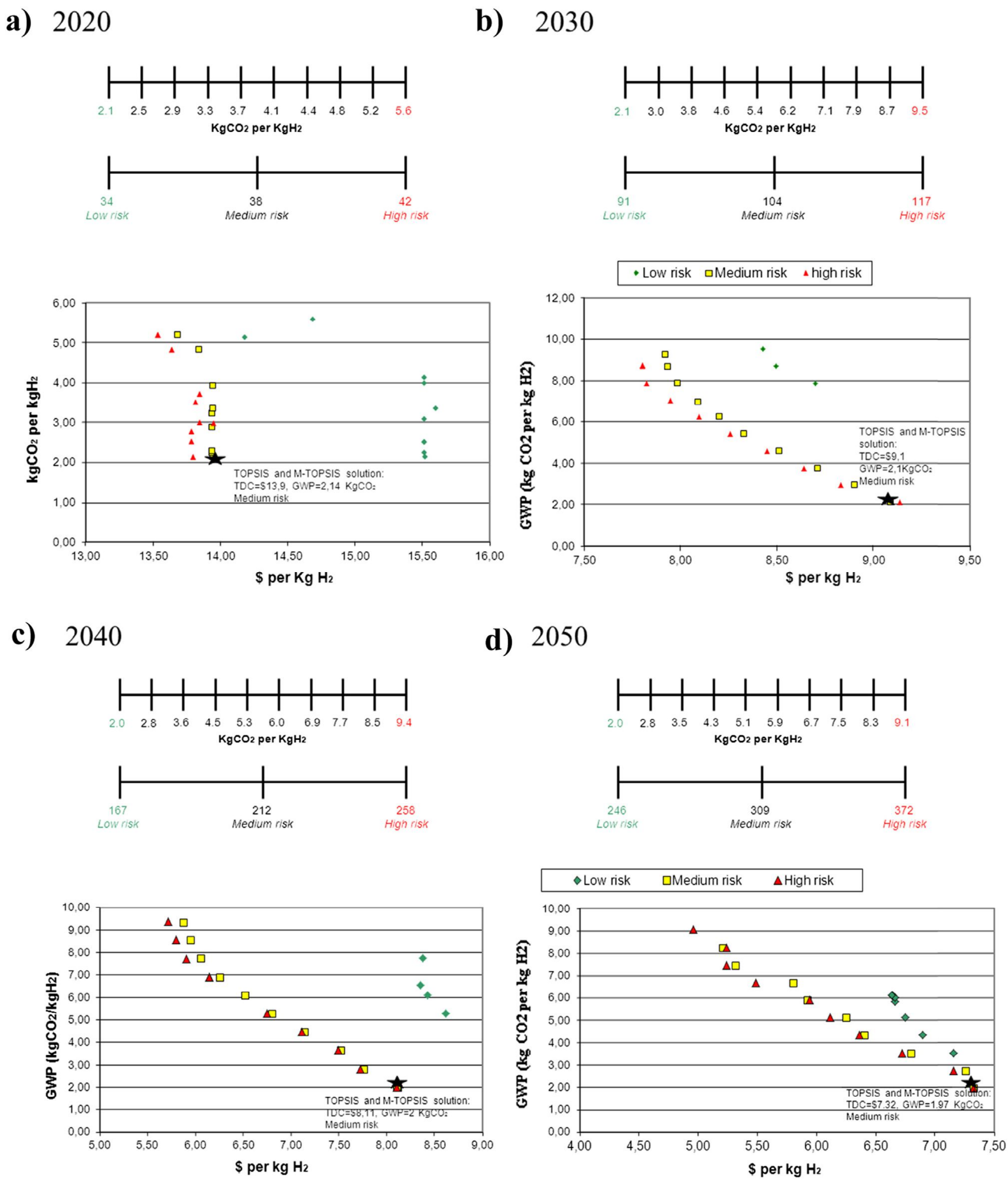

Fig. 6 – Pareto fronts for the multi-objective model for *case B* (four mono-period problems).

factor 5 on CO_2 in 2050 with a cost of \$7.3 per kg H_2 with respect to the cheapest option (around \$5 per kg H_2), (see Fig. 9).

In Fig. 9, the emissions related to HSC are compared to those of gasoline and diesel fuels. Only well-to-tank emissions need to be considered for FCEV. The average emissions of vehicles in France from gasoline and diesel cars are taken from Ref. [31]. The hydrogen would fulfil with the planned EU regulation being under 113 g CO_2 per km by 2020 but an important contribution would result from the configuration from the GWP minimization as well as the multi-objective *cases A* and *B* with emissions of 19 g CO_2 per km for H_2 fuel against 220 g CO_2 per km for the gasoline cycle, implying a reduction of 91%. Let us remember in this context that the

Table 4 – Multi-objective optimization results of the hydrogen supply chain (case B).

Year	2020	2030	2040	2050
Demand (kg per day)	7898	59,430	138,790	198,170
Number of production facilities	24	59	89	120
Number of storage facilities	44	90	159	213
Number of transport units	–	–	2	3
Capital cost				
Plants and storage facilities 10^3 \$)	235,231.9	632,143.9	963,670.4	671,306.4
Transportation modes (10^3 \$)	0	0	100	1500
Operating cost				
Plants and storage facilities (10^3 \$ per day)	56.2	395.1	896.3	1282
Transportation modes (10^3 \$ per day)	0	0	0.5	0.9
Total operating cost (10^3 \$ per day)	56.2	395.1	896.8	1282.9
Total cost				
Total network cost (10^3 \$ per day)	110.1	540.1	1125.7	1450.8
Cost per kg H_2 (\$)	13.9	9.1	8.1	7.3
Production facilities (10^3 t CO_2-equiv per day)	11.3	85.2	179.1	249.8
Storage facilities (10^3 t CO_2-equiv per day)	5.6	41.8	97.7	139.5
Transportation modes (10^3 t CO_2-equiv per day)	0	0	0.9	1.6
Total GWP (10^3 t CO_2-equiv per day)	16.9	127	277.6	390.9
Kg CO_2-equiv per Kg H_2	2.1	2.1	2.0	2.0
Production facilities risk	6	16	29	40
Storage facilities risk	32	86	167	223
Transportation modes risk	0	0	10	13
Total risk (Units-level)	38	102	206	277

French government adopted a Climate Plan to divide by 4 the French GHG emissions by 2050. For the case of cost minimization, emissions are close to the target. In this study, carbon capture and storage (CCS) has not being considered in the input configuration and this could constitute an option to be explored to reduce the environmental impact.

The multi-objective problem dimension treated in *case A* was compared with *case B* considered in our work (see Table 6). The criterion of computational time is not sufficient to select a method: the computational effort is also required for the creation of the pay-off tables. For *case A*, three mono-objective optimization needed around 13 h (mainly due to the TDC minimization), then the ε-constraint method with five ε-points for the GWP and five for the risk took around 3 h for calculation. The Pareto front and M-TOPSIS analysis finally took around 1 h. Globally, around 18 h are needed for obtaining results in *case A*. For *case B*, three optimizations for each criterion to create the pay-off table through lexicographic optimization were executed (36 calculations). The application of the ε-constraint method took several hours to solve the four mono-period problems. Globally, around 3 days are necessary for obtaining results in *case B*.

Conclusions and perspectives

In this paper, the HSC was designed for the Midi-Pyrénées region through the project "Green H_2 fuel" to evaluate the

Table 5 – Comparison of results among mono-objective cases (De-León Almaraz, Azzaro-Pantel, Salingue, et al., 2013) and multi-objective results for *cases A and B*.

	Solution strategy	Pay-off table obtained by mono-objective optimization. (Multi-period)			Case A. All criteria (multi-period)	Pay-off table obtained by the lexicographic optimization (mono-period)			Case B. Sequential (Mono-period)	Difference between A and B
2020	Cost per kg H_2 (\$)	**16.2**	24.5	17.5	23.4	**13.4**	15.6	14.7	13.9	−41%
	Kg CO_2 per Kg H_2	6.9	**2.1**	8.8	2.1	5.1	**2.1**	5.6	2.1	0%
	Total risk (Units)	35	42	**35**	35	42	35	**35**	37.5	7%
2030	Cost per kg H_2 (\$)	**8.4**	14.0	11.4	10.8	**7.9**	9.6	8.1	9.1	−16%
	Kg CO_2 per Kg H_2	10.6	**2.1**	9.6	2.1	8.9	**2.1**	9.7	2.1	0%
	Total risk (Units)	113	98	**89**	93	123	84	**83**	102	11%
2040	Cost per kg H_2 (\$)	**4.0**	7.8	5.7	7.2	**5.2**	8.3	6.9	8.1	13%
	Kg CO_2 per Kg H_2	10.8	**2.0**	8.6	2	10.1	**2.0**	8.5	2	0%
	Total risk (Units)	187	125	**107**	125	283	133	**117**	206	65%
2050	Cost per kg H_2 (\$)	**3.7**	9.2	5.6	6.7	**4.3**	7.6	5.8	7.3	9%
	Kg CO_2 per Kg H_2	10.9	**1.9**	8.5	1.9	10.3	**2.0**	8.5	1.9	4%
	Total risk (Units)	263	141	**112**	152	360	163	**146**	277	82%

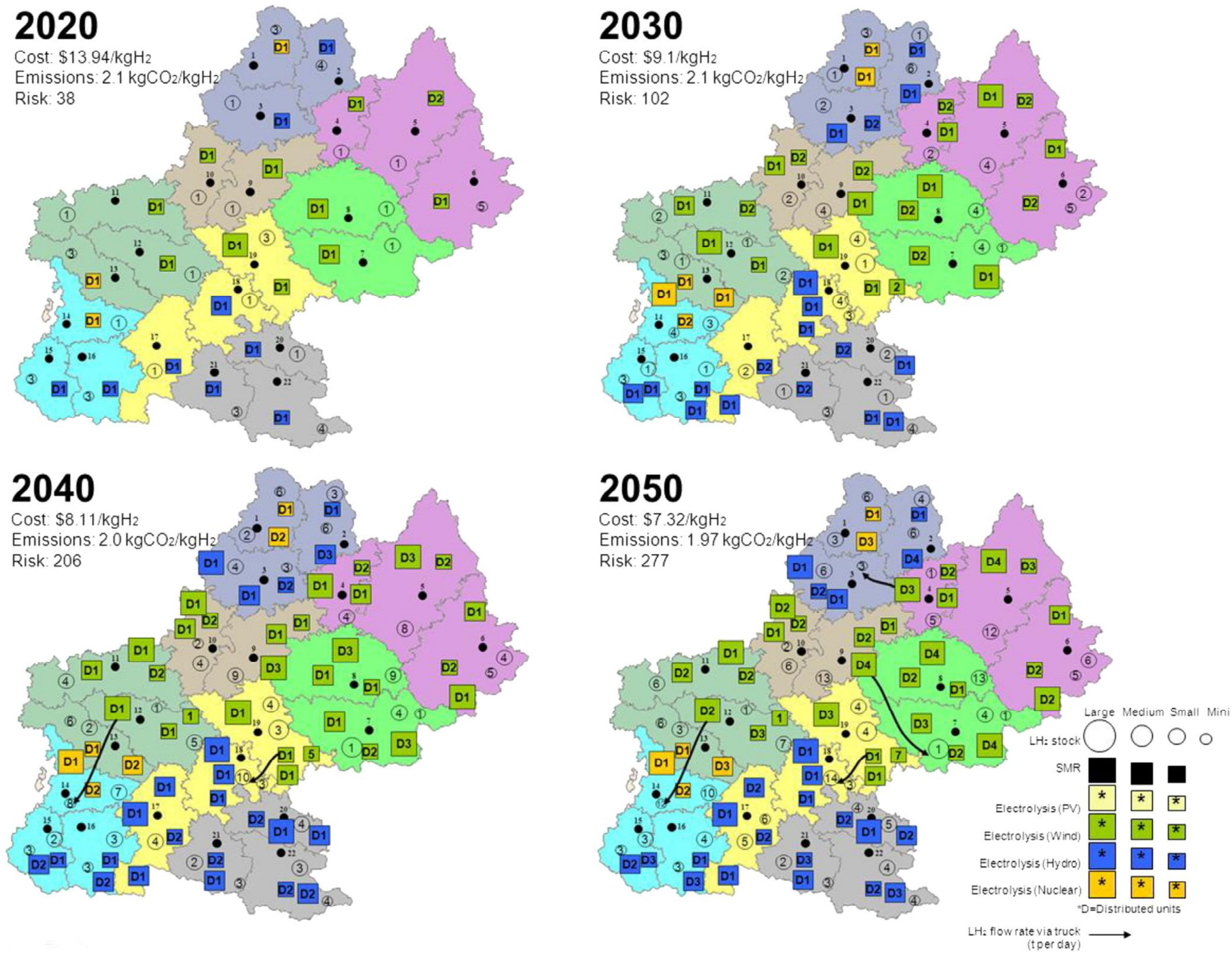

Fig. 7 – Network structure of liquid hydrogen distributed via tanker trucks. *Case B*: multi-objective optimization through lexicographic and ε-constraint in a low demand scenario in the Midi-Pyrénées region.

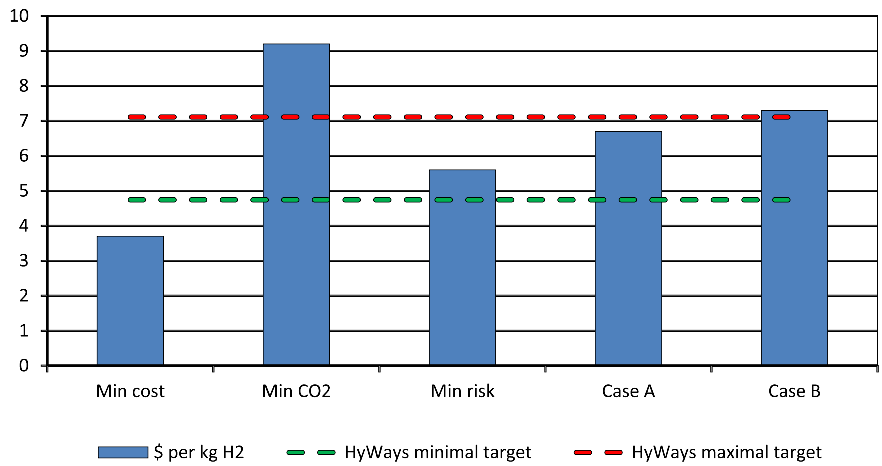

Fig. 8 – Cost per case in 2050 ($ per kg H_2).

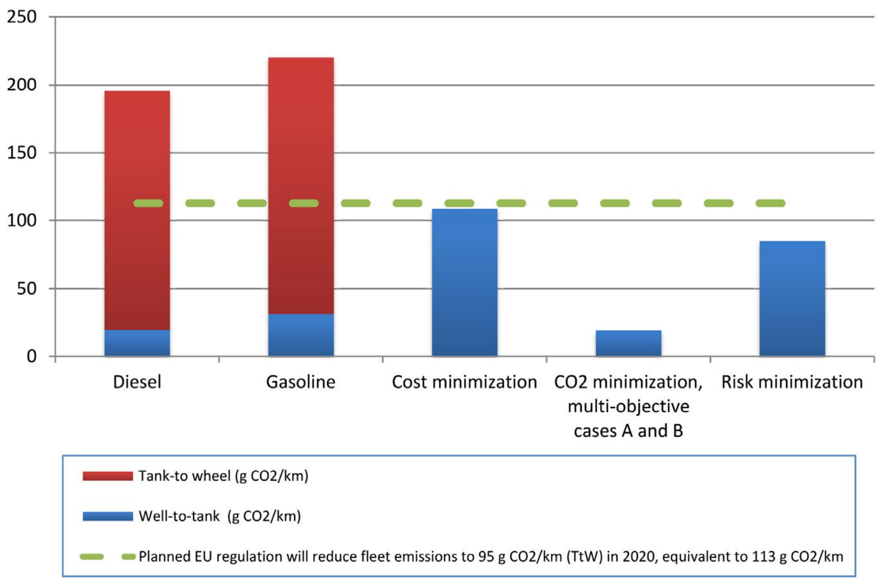

Fig. 9 – Comparison of emissions by sector in 2050 (Data from gasoline and diesel: (ADEME 2010)).

potential of H_2 to be used in FCEV in the time horizon from 2020 to 2050. The mathematical model presented in Refs. [21,30], was extended to the regional case study and considered the available energy sources and refuelling stations for a multi-period problem. Two solution strategies were taken into account involving global and sequential multi-objective optimizations. *Cases A* (ε-constraint method in a multi-period problem: global approach) and *B* (sequential-mono-period problem solved by lexicographic and ε-constraint methods) were compared when three objectives (cost, CO_2 and risk) were optimized.

For *case A*, the cost in the first time period is prohibitive. One of the main problems found in this approach is that the integration of the four time periods does not allow treating a specific time period. A better option for the 2020 period is given by *case B* having good results for GWP and risk but the cost is still high (\$13.9 per kg H_2). In *case B*, the TOPSIS choice seems to give preference to the GWP criterion but results are logical because of the reduction of CO_2 emission (the gain is of a factor 5 on CO_2) with a low impact in the cost. Moreover, the availability of RES promotes its use in the region. It can be concluded that transportation contributes mainly to the risk index.

Figs. 5 and 7 show the HSC configurations positioned in a geographical map, locating the production/storage facilities and flow rate via tanker truck in the corresponding district but not in the precise place. If a more detailed study is needed for operational phase, a spatial-based approach could be used and with this tool, a more realistic snapshot through a geographic information system software can be built as reported in Ref. [32]. In addition, new constraints concerning the geographic features might help decision making.

One perspective to find more competitive results is to consider a different geographic breakdown. In this work, only a regional French case was treated, but the design of the HSC at national scale remains mandatory.

Table 6 – Size of the treated examples (*cases A and B*).

Case	A	B
Number of constraints	205,057	50,564
Number of continuous variables	31,255	7816
Number of integer variables	11,088	2772
Computational time (hour)	18	72

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.ijhydene.2014.05.165.

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