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Renewable hydrogen supply chain for transport application in Corsica island

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Abstract

This paper aims to present an optimization approach for the design and planning of a hydrogen supply chain in Corsica Island. The formulation developed is based on a multi-period approach using a Mixed Integer Linear Programming (MILP) methodology. Three configuration scenarios of the Hydrogen Supply Chain (HSC) considering three single objective case studies are investigated related to the minimization of the total daily cost, of greenhouse gas emissions and of a risk-based index, respectively. The production of hydrogen is expected to cover the future demand of the fuel cell electrical vehicles (FCEVs) fleet planned for the 2030 period. The key innovation proposed here is to reconcile design and strategic planning over a short period using monthly fluctuations of hydrogen demand according to the predicted fuel consumption of the territory. The single objective optimizations for the case study show a decentralized distribution of production, storage and distribution units across the territory, with a lowest hydrogen cost of 8 €/kg during the period of high demand. This approach can be used to explore appropriate incentive mechanisms to boost the hydrogen economy in an isolated territory.

Keywords: Hydrogen, optimization, low-carbon fuel, Mixed-Integer Linear Programming, isolated area.

1. Introduction

The urgency to fight climate change has stimulated more and more interest in shifting investments from fossil-based energy to renewable sources. In that context, islands could play a key role in global development by becoming perfect places for demonstration of new clean technologies and pathways for sustainable development (Krajačić et al., 2008). In these isolated territories, the impact of the fossil fuel price is even higher due to its transport and their grid network is less stable. These reasons make the grid management more difficult and increase the cost of electricity production (Lamas, 2016). The massive integration of renewable energies (RE) on the small island grids could further increase the disturbances between production and demand because of their intermittency. In that context, hydrogen can be viewed as an “energy vector” and play a major role in decarbonization if generated by electrolysis using renewable energy surplus (Krajačić et al., 2008). Due to actual hydrogen demand scale, today investments remain yet too risky for wide-scale green hydrogen production that could compress costs, creating the so-called chicken-and-egg problem.

According to several studies, the economic viability of a hydrogen production system associated with renewable energy sources depends strongly on the identification of an

optimal configuration of the hydrogen supply chain (HSC) (Seo et al., 2020; Won et al., 2017). The HSC design has been mostly studied at the strategic/tactical level compared to the operational levels. The inputs of such models are constituted by a set of options for the production, storage and transportation, while the outputs are relative to the type, number, location and capacity of the production, storage and transportation units. Most works devoted to hydrogen supply chain modelling are based on mathematical programming approaches, mainly Mixed Integer Linear Programming (MILP) and generally limited to single objective (cost minimization) (Won et al., 2017) or bi-criteria assessment, i.e., cost-environment or cost-risk (Kim and Moon, 2008). These contributions generally involve a rolling horizon approach in which the overall horizon is divided into strategic periods during which capital investments are made at the very beginning and which can last up to 10 years. The decision variables made at a given period are then coupled over the large time-span, since the optimization strategy is viewed globally. As reported in (Agnolucci et al., 2013) only a few infrastructure optimization studies explored the spatial and temporal dynamics of demand which was identified as a key sensitive parameter with sources of uncertainty that can be addressed by a stochastic approach (Kim et al., 2008).

The objective of this work is to demonstrate deployment of hydrogen technologies in an integrated manner in a remote territory, here Corsica Island. The formulation is based on the previously developed long-term MILP approach for HSC infrastructure design (De Leon Almaraz, 2014). The key innovation we propose here is to extend this framework to the combined design and planning over a shorter period using monthly fluctuations of hydrogen demand according to the fuel consumption of the territory.

2. Presentation of the methodological framework

2.1. Principles

The methodological framework for the design and operation of a future HSC is treated regarding a geographical and multi-period approach in order to supply hydrogen demand profile of a given geographic area. The optimization problem was formulated as a Mixed Integer Linear Programming (MILP) model using GAMS[®] modeling system with CPLEX 12 solver (De Leon Almaraz, 2014). Three optimization objectives are considered in this study: an economic criterion that consists of the minimization of the total network cost, both in terms of capital and operating expenditures, an environmental criterion related to the global Greenhouse Gas (GHG) emissions of the supply chain and a risk index (Kim and Moon, 2008) subject to: supply, demand, mass conservation and technical performance. A set of techno-economic parameters is considered: production, storage, and transport options, possible locations, available energy sources, capital and operation cost, technical features (efficiency, capacity, lifetime, load factors, storage capacities) and GHG emissions of the various technologies. Several constraints are involved considering continuous, integer and binary variables. The integer decision variables represent the location of facilities, sizing decisions and the selection of suitable production technologies and of transportation modes between facilities. The binary (respectively continuous) variables indicate the hydrogen transport direction (respectively flows). The model then provides as outputs the HSC optimal configuration.

2.2. Model assumptions

The assumptions of the model can be summarized by:

- The territory is divided into grids;
- Production units can only be installed on specified grids;
- Only photovoltaic (PV) and wind power are considered for energy sources;

- Hydrogen is produced only by electrolyzers and supplied in gaseous form;
- Only transport by tanker-trucks may exist between grids;
- Produced hydrogen is dedicated to transport application and distributed via refueling stations.

2.3. Mathematical formulation

The novelty of this work is based on the use of finer grains for time interval definition (i.e. monthly intervals) that require the definition of additional parameters such as the number of operating hours and the power of the electrolyzers.

2.3.1 Constraints

The total availability of primary energy sources in a grid g during time period t ($Atot_{gt}$) is given as a sum of three terms, that correspond to the initial average availability of renewable energy sources ($A0_{egt}$), the import of primary energy sources from the grid network ($IPES_{egt}$) and the rate of consumption of the primary energy sources (ESU_{gt}):

$$Atot_{gt} = \sum_e (A0_{egt} + IPES_{egt}) - ESU_{gt} \quad \forall e, t, g; g \neq g'$$

ESU_{gt} is equal to the product of gamma (γ_{pj}) the rate of utilization of primary energy source by the daily hydrogen production rate for each production plant type p and size j (PR_{pjigt}).
 $ESU_{gt} = \sum_{pji} (\gamma_{pj} \times PR_{pjigt}) \quad \forall g, t; g \neq g'$

The Energy Availability EA_{gte} is the product of the energy power source capacity in each grid during period t and for each energy source (ESP_{gte}) multiplied by the number of hours per month (Mh_t) and the capacity factor for each energy source (CF_{et}) divided by the total number of days per month (dM_t).

$$EA_{gte} = \frac{\sum (ESP_{gte} \times Mh_t \times CF_{et})}{dM_t} \quad \forall e, g, t; g \neq g'$$

The installation of production (IP_{pjigt}), storage (IS_{sjigt}), and distribution (IFS_{fsjigt}) units only occurs at the first period t .

$$IP_{pjigt} = 0, \forall t \neq 1; \quad IS_{sjigt} = 0, \forall t \neq 1; \quad IFS_{fsjigt} = 0, \forall t \neq 1;$$

The minimum and maximum daily production capacity ($PCAP_{pij}^{min}$) and ($PCAP_{pij}^{max}$) is respectively calculated by considering the lower and upper daily capacity factor of electrolyzer type p and size j given in hours per month (respectively $ELCF_{p,j,i}^{min}$ and $ELCF_{p,j,i}^{max}$) and the assigned power of each given electrolyser in kW ($PElec_{p,i,j}$). Nd is the number of days per month and gamma (γ_{pj}) is the rate of utilization of primary energy source (in kWh/kg).

$$PCap_{pij}^{min} = \frac{\left(\frac{ELCF_{pij}^{min}}{Nd}\right) \times PElec_{pij}}{\gamma_{pj}}; \quad PCap_{pij}^{max} = \frac{\left(\frac{ELCF_{pij}^{max}}{Nd}\right) \times PElec_{pij}}{\gamma_{pj}}; \quad \forall p, i, j$$

2.3.2 Objective functions

The monthly average cost of hydrogen ($Mcost_t$) is determined by summing the capital costs of all units over the lifetime of the units (lf) with the maintenance and operating costs ($Opex_t$) of the units over the sum of the total demand for each grid g of product type i in time period t (DT_{igt}) multiplied by the number of days per month (dM_t).

$$Mcost_t = ((Capex_t \div lf) + Opex_t) / \sum_{ig} (dM_t \times DT_{igt}); \quad \forall e, g, t; g \neq g'$$

The total global warming potential is determined from the total daily greenhouse gas (GHG) emissions of the production, storage and transport units. Similarly, the relative

risk of hydrogen activities is determined by risk ratings calculated based on a risk index method including the risk of production, storage and transport (Kim and Moon, 2008).

2.4. Study case

2.4.1 Demand evaluation

Corsica is a French region that is greatly impacted by tourist activities. According to the annual evolution of the fuel consumption in the island, 2.5% of the equivalent energy could be substituted by hydrogen fuel in 2030 (“Le Schéma Régional Climat, Air, Energie (SRCAE) de Corse,” n.d.). This corresponds to a daily hydrogen demand ranging from 4.3 t/day in January to 8.1 t/day in August. The fluctuating hydrogen demand expressed in energetic values is presented in figure 1.

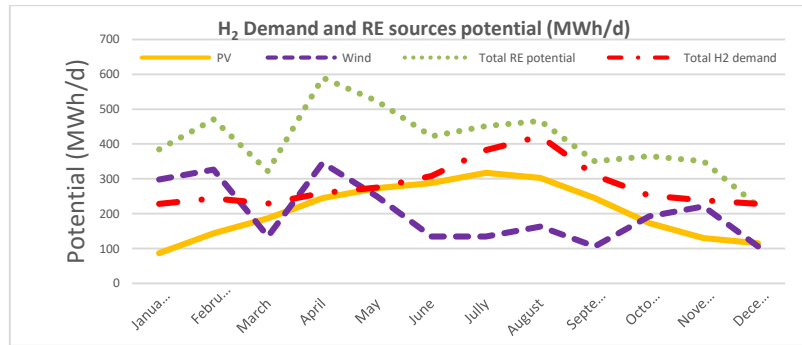


Figure 1: H₂ Demand and RE source potential

2.4.2 Techno-economic parameters

Table 1 presents the minimum and maximum values of the most significant parameters for production, storage, transport and distribution units.

Min-Max	Production unit	Compressor unit	Storage unit	Transport unit	Distri. unit
Capacity	300-5000 (kW)	126 (kg/h)	50-30000 (kg)	670 (kg)	20-1300(kg/d)
CAPEX	1038-3500 (€/kW)	635 (€/kW)	500 (€/kg)	746 (€/kg)	410-1480 (k€)
O&M	0,11-0,20 (€/kg)	0,007 (€/kg)	0,006-0,02 (€/kg)	trip dependent	0,15-0,39 (€/kg)
Efficiency	37,80-52 (kWh/kg)	2,66 (kWh/kg)	-	-	-

Tableau 1: Techno economic data of the production, storage, transport and distribution units

Two types of electrolysis technologies are used, i.e., Alkaline (AE) and Proton Exchange Membrane (PEM) electrolyzers, seen as the most suitable ones for the supply chain in Corsica as they are mature technologies and do not require large heat sources to operate.

2.4.3 Energy sources (cost and potential)

The cost projections used in this work assume that renewable energies will cover 87% of the French electricity demand in 2050 and that 70% of the French nuclear park will be kept. This hypothesis projects the cost of electricity produced by PV and wind power at respectively 16 €/MWh and 35 €/MWh in 2030.

The power generation capacity of the renewable energy sources (PV and wind respectively 60 MW and 40 MW) allocated to the production of hydrogen has been determined according to the available resources on the island and the capacity factor of each technology. Figure 1 shows the forecasted production of these sources for year 2030.

3. Results and discussions

The territory is divided into 9 grids for this study. The results of the simulations show that the model has treated a total of 134308 single equations, 53861 single variables and 24192 discrete variables. The single optimization run led to a maximum CPU time 22s for an instance with CPLEX solver provided with Gams 28.2 (using 7 threads of an Intel Core i5 computer). Figure 2 shows the distribution of the different types of electrolyzers selected and the value of each objective function for each optimization case. The number, size and technology chosen for each configuration is different depending on the objective function used. Large production, storage and distribution units are the most used to reduce the operating cost by mutualizing the maintenance and operation costs. The average production cost obtained is the lowest 12.19 €/kg against 28.03 €/kg and 26 €/kg for the GHG and risk criteria respectively (i.e. expressed as a monthly average cost of production that differs from the levelized cost of hydrogen (LCOH) which takes into account the life cycle of the plant and the discount rate). This cost evolves according to the monthly production rate of hydrogen and the availability of energy sources, reaching its lowest value in August, i.e. 8 €/kg.

A total of 6 transport units are found with cost optimization and one less for the other criteria. The transport from zone 7 to 1 has been replaced by a production unit directly located in zone 1.

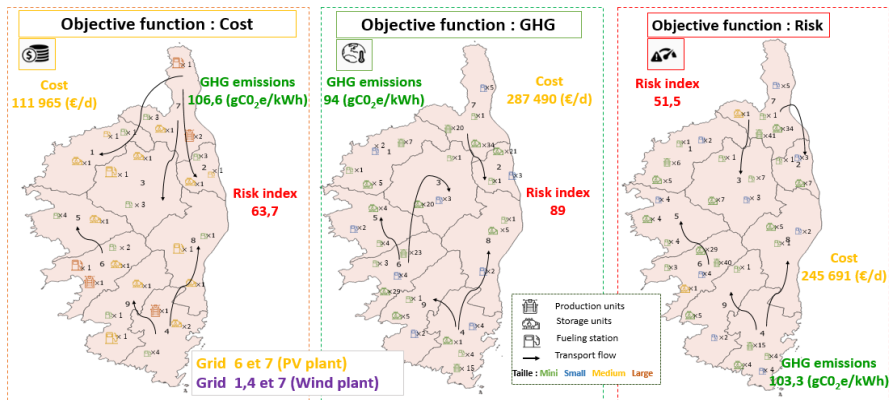


Figure 2: Hydrogen supply chain configuration

The objective based on minimizing GHG emissions leads to a more decentralized configuration with much smaller equipment and more efficient alkaline-type electrolyzers. The amount of GHG emissions is 94 gCO₂e/kWh and although logically most favorable compared to the other criteria, the gap is not significantly high compared to the result obtained with the cost criterion since the technologies considered for hydrogen production involve a green energy mix. Finally, when the optimization criterion chosen is to reduce the total risk index, almost all the equipment chosen are of minimal size because they present less risk. The risk index at this level is 51.5 against 67.3 and 89 for the cost and GHG emission criteria respectively.

According to the season, the distribution of hydrogen can vary. In winter, the distribution rate is at a minimum (670 kg/truck) while in summer it reaches almost 1t/day with no additional transport units. Although the demand in zone 7 is the highest, it provides 56% of the hydrogen supply due to its high production potential. Figure 3 shows the distribution rate for the cost criteria in January and August.

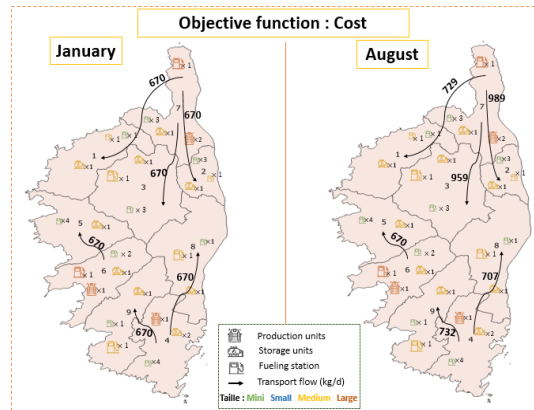


Figure 3: hydrogen distribution during winter and summer

Since photovoltaic energy is the cheapest, it is used up to 74% for the production of hydrogen in order to obtain the most affordable costs. However, the use of photovoltaic energy is still higher than wind energy even for the two other criteria (56% and 65% for the GHG and risk criteria respectively) since the availability of solar energy is higher during periods of high consumption. Photovoltaic power plants are only available in grids 6 and 7 and wind power plants only in grids 1, 4 and 7.

4. Conclusion and perspectives

This paper presented a methodological framework for the design and operation of HSC in Corsica island considering monthly variations in demand. The single objective optimizations for the case study show a decentralized distribution of production, storage and distribution units across the territory. The production cost is still quite high compared to large-scale production chain, but this approach can be used as a framework to support authorities to invest in this field in isolated areas. The next step of this work is to look for the optimal configuration for the three optimization criteria taken simultaneously (multi-objective optimization). This approach can be used to explore appropriate incentive mechanisms to kick-start the hydrogen economy in an isolated territory since the hydrogen cost still remains high even when cost minimization is considered. This optimization approach can also be extended by integrating the geographical and topographical constraints of Corsica.

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