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Multiobjective and social cost-benefit optimisation for a sustainable hydrogen supply chain: Application to Hungary

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HIGHLIGHTS

- New multiobjective optimisation model to design a sustainable hydrogen supply chain.
- Optimisation of LCOH, GWP and safety risk and social cost-benefit.
- Methodology applied to the “Green H_2 in Hungary” project.
- H_2 demand for industrial and mobility markets (trucks and buses).
- Comparison of single- and multiobjective optimisation strategies.

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ABSTRACT

This article presents a comprehensive approach to design hydrogen supply chains (HSCs) targeting industrial and mobility markets. Even if the inclusion of sustainability criteria is paramount, only a few studies simultaneously consider economic, environmental, and social aspects - the most difficult to measure. In this paper, the safety risk and the social cost-benefit (SCB) have been identified as quantifiable social criteria that would affect society and the end-users. The objectives of this research are (1) to design a sustainable HSC by using four objective functions, i.e., levelized cost of hydrogen, global warming potential, safety risk and social cost-benefit through a mixed-integer linear programming model; (2) to compare results from SCB and multiobjective optimisation. The integration of the SCB criterion at the optimisation stage is not a trivial task and is one of the main contributions of this work. It implies the minimisation of the total cost of ownership (TCO) for buses and trucks. The evolution of the HSC from 2030 to 2050 is studied through a multiobjective and multiperiod optimisation framework using the ε-constraint method. The methodology has been applied to a case study for Hungary with several scenarios to test the sensitivity of demand type and volume as well as the production technology. The results analysis highlights that (1) it is beneficial to have mixed demand (industry and mobility) and a gradual introduction/migration to electrolysis technology and fuel cell vehicles (FCVs) for a smooth transition. Liquid hydrogen produced via water electrolysis powered by nuclear and wind energy can result in an average levelized cost of \$4.78 and 3.14 kg CO_2-eq per kg H_2; (2) the frameworks for multiobjective optimisation and SCB maximisation are complementary because they prioritise different aspects to design the HSC. Taxes and surcharges for H_2 fuel will impact its final price at the refuelling station resulting in a higher TCO for FCVs compared to diesel buses and trucks in 2030 but the TCO becomes almost competitive for hydrogen trucks from 2035 when SCB is maximised. The SCB function can be refined and easily adapted to include additional externalities.

1. Introduction

The energy sector is facing a critical moment related to demand and global environmental issues [1]. The European Commission has established agreements and guidelines to achieve climate neutrality by 2050 [2–3], all in accordance with the Paris Agreement, which aims to limit

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global warming to 1.5 °C [4]. The European Green Deal, through the "2030 Climate Target Plan", intends to increase the greenhouse gas emissions reduction from the 40 % target to a 50–55 % reduction compared with 1990 levels [2–3,5–6]. The European Green Deal has published its "Fit for 55" package to enable the EU to meet those targets. The convergence of these initiatives with the COVID19 pandemic has resulted in recovery plans and economic stimulus with a focus on clean resilience systems [1,7]. While decarbonisation is a key issue in the energy transition, energy consumption will continue to grow [8], and there is an urgent need to work on energy security and to accelerate the energy shift to have affordable and clean energy [9]. Renewables' intermittency has been a limitation to the penetration of renewable energy sources (RES) in the energy mix. To meet this challenge, hydrogen (H_2) represents a promising alternative to balance electricity generation and its consumption by recovering the electricity surplus (e.g. from photovoltaic (PV) and wind parks), creating greater flexibility in energy systems [10].

Hydrogen has been already mentioned in several roadmaps as a crucial energy carrier [7,11–12]. It can be used in fuel cells (FC) for both mobile and stationary applications to generate electricity. Hydrogen competitiveness, especially when sustainability is targeted, depends on several factors, e.g., demand and market type, available infrastructure, technology type and readiness, available energy resources, regulation, safety, education (know-how), social acceptance, etc.

In industry, hydrogen is currently used in ammonia plants, refineries, chemical industry, etc., and there is also a big potential for hydrogen to be used in energy-intensive industries: iron-steel and cement sectors, partially motivated by more expensive CO_2 allowances [13–14].

For mobility, a significant demand increase is expected for H_2 in cars, buses, drones, heavy-duty trucks, trains and airplanes [13]. COP26 has reached a regional agreement "to make zero-emission vehicles the new normal by making them accessible, affordable and sustainable in all regions by 2030 at the latest" [15], with electric and fuel cell vehicles as the main competitors in this category. Moreover, one of the regulatory proposals adopted by the European Commission is to amend the mandatory carbon dioxide (CO_2) emission targets for new passenger cars and light commercial vehicles (vans) [16] to promote the technology switch. Recent efforts in Europe have allowed the installation of refuelling stations in several countries, and there are incentives for pilot projects for stationary options (e.g. H_2 valley platforms) [17].

The road freight sector is an important pillar of the European economy as 75 % of goods are transported on wheels, but it also has an important contribution to carbon emissions [18]. Heavy-Duty Vehicles (HDV) can include trucks and buses and constitute a key sector to decarbonise. Purchase prices for Fuel Cell Electric Buses (FCEB) are decreasing from 650 k EUR in 2020 to 500 k EUR in 2023 [17], and these are at a commercial stage. In the European Union (EU-28), HDV account for approximately 27 % of road transport-related CO_2 emissions [19]. Heavy-duty trucks (HDTs) are used mainly for logistics and supply chain for goods and cross several EU countries using the European corridors. Fuel Cell Heavy-Duty Trucks (FCHDT) have been widely promoted to replace diesel trucks. Today, there are prototype trucks for on-road demonstrations, but the commercialisation is still at an early stage. The market penetration is an important variable because the demand for both trucks and hydrogen will impact the Total Cost of Ownership (TCO) [18], but the limited refuelling infrastructure and the Levelized Cost of Hydrogen (LCOH) can affect the market share. However, Ruf et al. [18] found that with scaled-up production of FCHDT and hydrogen offered below 6 EUR per kg [~$6.8], FCHDTs provide the operational performance most comparable to diesel trucks regarding daily range, refuelling time, payload capacity, TCO and can become cost-competitive by 2027. In the EU, there are plans to have 80,000–100,000 hydrogen trucks and 1,000 hydrogen stations by 2030 [17,20]. For this purpose, the European industrial sector is working on research and development to achieve these goals (e.g. Shell is working with Daimler truck and Volvo group to create the conditions for the mass market introduction of FCHDT) [21], while some corridors also start to install hydrogen refuelling stations (e.g. "Corridor H_2" in Occitanie") [22].

Moreover, the European Commission [23] has announced an ambitious goal to bring the hydrogen cost below 1.8 EUR per kg by 2030 [~$2] and to increase Europe's annual production of green hydrogen to 10 million tonnes by 2030 [17,24] by installing at least 6 GW of renewable hydrogen electrolysers in the EU by 2024 and 40 GW of renewable hydrogen electrolysers by 2030 [24]. From these objectives, there are two important analysis points. The first one is related to the availability of renewable sources in Europe and the amount that can be used to produce H_2 on a large scale. This requires a consistent plan to develop RES and hydrogen supply chains (HSC) simultaneously. Hydrogen imports would affect a country's energy dependency; therefore, this has to be carefully considered in any development plan; there are a number of regions where hydrogen imports could be cheaper than domestic production [25]. The second one is related to the LCOH and carbon emissions that depend, among other aspects, on the technology used in the supply chain (from the energy source to distribution) in different countries. The wide variety of technological options offers the possibility of producing hydrogen everywhere, but this does not systematically involve a vision of sustainable development and makes decision-making more complex. A key point in the development of the sustainable HSC is the demonstration of feasibility while many technical, economic and social obstacles must be overcome [10,26].

Some roadmaps have started to explore the hydrogen potential in Central and Eastern Europe [18–19]. In this study, the case of Hungary will be analysed. Hungary has a clear interest in reducing its demand for energy imports and simultaneously ensuring its connection to the regional electricity grids and natural gas networks, which guarantees the security of supply and effective import competition [12]. Hungary has already a Hydrogen National Strategy [27] and announced several H_2 pilot projects (e.g. Black Horse,[1] H_2 valleys, "Green Truck", refuelling stations along corridors,[2] etc.) and its commitment to address regulatory barriers [28] as well as plans to establish appropriate conditions (including safety) and incentives necessary to inject hydrogen into the natural gas system [13]. With a population of almost 10 million people and an area of 93,030 km^2 [29], Hungary uses 44 % of the energy in the road sector with trucks, buses and light commercial vehicles and identifies the use of both electric vehicles and FCVs as opportunities to decarbonise mobility [28]. Hungary's location is strategic for goods logistics because it connects West and East Europe. Hungary is also working with the other Visegrad countries (Slovakia, Czech Republic and Poland) to have a coordinated plan [30]. The Hungarian National Energy and Climate Plan (NECP) has reported that about 1 % of its transport needs would be covered by hydrogen in 2030 and around 5 % in 2040 [12,13]. In the NECP, some scenarios already display a potential consumption of "clean" hydrogen with a low-demand market share from 2026 [12].

The European and National roadmaps provide useful guidelines; however, approaches for the strategic and operational deployment of the supply chain are also needed. Several mixed integer linear programming (MILP) models have been proposed to design the HSC. The great majority of optimisation studies presented in Section 2 address mainly techno-economic or environmental aspects. There are also multiobjective optimisation models that include, e.g., the total daily cost, the CO_2 emissions and the risk in the optimisation [31–33]. However, up until now, the social aspects have been rarely treated in works using multiobjective optimisation for HSCs and have been mainly

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[1] The Black Horse project will see the development, installation and operation of a hydrogen eco-system in the Czech Republic, Hungary, Slovakia and Poland. A network of 270 HRS (for HDV, buses and passenger cars) will be set up to provide the infrastructure for the planned deployment of 10,000 FCHDTs [18].

[2] TEN-T corridors, Helsinki corridors [27].

related to the minimisation of safety risk, carbon emissions or air pollutants [34–37]. At this point, where the potential users' might ask, "is it worth switching my diesel HD truck to a FC one?", it is important to include practical social criteria, like the vehicle's TCO to design networks where the buses or trucks might become commercially viable, and where the H_2 price must be competitive with the price of fossil-based fuels. The social cost-benefit (SCB) could be a useful measure because it can include the TCO, the vehicle's purchase price, the fuel cost, the platinum cost, carbon prices, noise cost, etc. To the best of our knowledge, from the few studies that have analysed the SCB for the HSC (or some of its elements), none has included it as part of the optimisation stage (only post-optimal or scenario analyses were performed) [18,26,38]. This is an important research gap to be covered because minimising only the environmental impact of the HSC may not result in a LCOH being economically competitive with fossil-based fuels (and vice-versa), and just measuring the SCB does not have an impact on the output configuration. To contribute to filling this gap, the novelty of this work is the inclusion of the SCB as first proposed by Cantuarias-Villessuzanne et al. [38] as part of the optimisation stage of the HSCs. It includes the cost and environmental impact from the user's point of view and the platinum depletion. To our knowledge, this is the first work that includes the SCB with TCO in a multiobjective optimisation model for the HSC.

The scientific objective of this paper is to design a sustainable HSC within an optimisation approach, combining engineering and social concepts. More precisely, this paper involves a mathematical approach to design the HSC for Hungary by using multiobjective optimisation techniques. Several scenarios are explored with variations in the demand market (industry and mobility) and in the technological options (steam methane reforming (SMR), electrolysis or both). A multi-period approach of five 5-year periods (2030–2050) is proposed considering sustainability criteria including economic, technological, environmental and societal aspects. Our previous works [33–34,39] have been taken as a reference, but a new model is proposed to adapt to the latest conditions and include new optimisation functions, i.e., the total daily cost function will be replaced by the LCOH, and the social aspects will be studied from the safety and SCB perspectives. The environmental part is given by minimising the GWP. Our contribution to the existing body of knowledge thus consists of (1) the inclusion and optimisation of the SCB with TCO in the HSC model, (2) the comparison of the results of multi-objective optimisation by using the ε-constraint method on the one hand, and those of the SCB maximisation on the other hand with the methodology and model applied to Hungary. This research has been developed in coordination with three research groups: the Corvinus Institute for Advanced Studies, the Regional Centre for Energy Policy Research and the Chemical Engineering Laboratory (*Laboratoire de Génie Chimique*-LGC – *Université de Toulouse*) and will be referred to as "Green H_2 in Hungary".

The remainder of this paper is organized as follows: in the next section, the literature review is presented. The problem statement is described in Section 3 followed by the methodology (Section 4). In Section 5, the objective functions of the mathematical model are presented. Section 6 is dedicated to the solution strategies for the multi-objective problem and a design-of-experiment based frame for scenario definition. The optimisation results and subsequent discussion for all cases are presentedin Section 7. Finally, conclusions and perspectives are given.

2. Literature review

The literature review was guided by searching generic hydrogen supply chain models and reports with applications to Hungary. The document entitled "Opportunities for Hydrogen Economy Technologies Considering the National Energy & Climate Plans" [13,28] is an interesting approach that includes the assessment of different technologies in different territories and presents aggregated results in terms of cost, emissions, job creation, etc., providing recommendations to specific country's conditions. The Hungarian NECP [12] and the National Hydrogen Strategy [27] specify the targets. Other important international documents are those published by the IEA [25,40] and IRENA [41–43]. Despite the broad agreement that hydrogen could make a significant long-term contribution to energy policy goals, there is no single, shared vision of a "sustainable hydrogen economy" [10]. The European and National roadmaps are paramount at the strategic stage for the H_2 economy; however, there is a need for additional approaches to support the strategic and operational deployment of the supply chain. Since the lack of existing infrastructure is largely reported in the dedicated literature, one alternative to design the HSC is to use supply chain management tools. The management of supply chains is a complex task mainly due to the large size of the physical supply networks with their associated uncertainties and decisions that include [44]:

- number, size and location of production sites, storage and distribution centres, and the resources inside them;
- production decisions related to plant production planning and scheduling;
- network connectivity (e.g., allocation of suppliers to plants, storage units to markets, etc.);
- management of inventory levels;
- transportation decisions

The review shows that the most common approaches in designing and modelling the so-called HSC involve optimisation methods through mathematical models with some specific objective functions (e.g., economic, safety, environmental aspects).

MILP approaches have been widely used. The seminal work of Almansoori et Shah [45–46] introduced a general model that determines the optimal design of a network (production, transportation and storage) for vehicle use of H_2 where the network is demand-driven with application to a Great Britain case based on cost minimisation. Their subsequent publications have extended the model by considering the availability of energy sources and their logistics, as well as the variation of hydrogen demand over a long-term planning horizon. The economic aspect has been the main objective optimised in most of the HSC models. The Total Daily Cost [33,47] or the Net Present Value or Discounted Costs [37,48] have been used as an optimisation function. In more recent publications, especially in those including hydrogen in the power-to-gas sector [49–50], the LCOH is being used instead of the daily cost because it eases comparisons among different reports (e.g. [51–52]).

The spatial scales (e.g. national, local) for HSC studies have been widely examined with application of HSC optimisation to different countries or regions e.g. [31–32,37,47–48,53–54]. However, the level of detail of the geographical implications mainly depends on the technology and the location of the different units is not considered. However, some papers test the sensitivity of their models and assumptions by considering spatial and geographical constraints and using Geographic Information Systems [33,39,55–61].

Several studies have addressed issues related to the design and deployment of HSCs to find the most efficient HSC network by considering multiple criteria [31,33,45,48,56,62–68]. They are primarily based on techno-economic considerations such as the hydrogen cost and on environmental assessment mostly involving Global Warming Potential (GWP) indicator and, in a more systemic way, a life cycle assessment methodology [31] with a recent contribution that includes the Planetary Boundaries [69] adding a set of biophysical limits critical for operating the planet safely to a MILP model.

Socio-cultural criteria are often difficult to be quantified at earlier stages of development, so they are rarely integrated into design methodologies despite their importance. Large sustainability frameworks connect different dimensions, and these can be presented as in the Sustainability Development Goals [70] or measured through indices, e.g. World Energy Trilemma [71]. In a country, the social aspects require a holistic view, and some approaches include many dimensions, e.g. the Social Futuring Index aims to provide a normative framework through a measure applicable to countries comprising a number of dimensions and indicators to define a "Good life" or the wellbeing of a nation [72]. This study as other sociology ones include energy as an important variable that has an impact on society due to the high dependency developed and increasing in the last years. Another aspect that has been explored concerns the finite resources that are used for energy transformation while the human wellbeing, behaviour, habits and choices in different societies affect the energy generation and consumption and vice versa [72–73]. At a global level for a power system, Heras and Martín [74] included social indexes (e.g. unemployment rate, regional GDP and population density) in a model to determine the location of power facilities. "Multiobjective optimisation", has been proposed for hybrid renewable energy systems in the review papers from [75–76] where a set of technical, economic, environmental and socio-political objectives (acceptance, labour, social cost of carbon emissions, security of supply) were used [76]. Although these works list potential social criteria, the formulation of the social aspects is not given.

The pathway towards a hydrogen economy must include the three pillars of sustainability, and although there are macro studies that include social aspects in the analysis, there is a lack of information for the social assessment related to hydrogen that has been identified [77–79]. The public acceptance has been studied in descriptive studies with a focus on the comparison between diesel, gasoline and hydrogen cars by measuring user acceptance of the new car types and refuelling stations [80–82].

In MILP models, Dayhim et al. [36] used a Total Social Cost function to optimise a multi-period HSC network under uncertain daily demand where capital and operating costs are included as well as the emission cost ($/d). In this study, the demand for fuel cell vehicles is aggregated and based on different household attributes such as income, education etc. The monetary impact of environmental aspects has also been optimised in [37] (i.e., discounted cost of carbon tax and revenue of low-carbon fuel standard).

The safety risk index has been explored as a key social criterion that depends on technology but affects society [32–33,35,55]. Recent works are adding details about the demand type or market (e.g., H_2 for industry, mobility, etc.), and recently more papers are evaluating the potential demand of buses [83] and heavy-duty trucks [60,84] in the HSC models; however, the social aspects for this market is still only studied from the safety point of view.

Alternative approaches to MILP models have introduced some options for the evaluation of social aspects. Creti et al. [85] used cost-benefit analysis for FC cars in Germany at the horizon of 2050. Cantuarias-Villessuzanne et al. [38] developed a SCB analysis to estimate the period of transition from gasoline internal combustion engine vehicles to FCV to be socio-economically profitable considering different production technologies and two external costs: the abatement cost of CO_2 through FCV and the use of non-renewable resources in the manufacture of fuel cells by measuring platinum depletion. In [38], the TCO is calculated so that the running cost is affected by the hydrogen price. For HDV, Ruf et al. [18,86] report TCO for Heavy-Duty vehicles. These analyses are based on Excel calculations.

Recently, Ochoa Robles et al. [26] calculated the SCB from the output results of a HSC MILP model as a post-optimal calculation. Although this approach can be useful for calculating both the TCO for mobility and SCB, the social-cost criterion is not considered as an objective function of the optimisation procedure. Similarly, Shamsi et al. [87] use an optimisation model to design the HSC and then quantify the health benefit from the pollution reduction (using the Motor Vehicle Emission Simulator) to show the potential social and economic incentives of using FCEVs.

There is a need for a more holistic approach to link fuels to their social cost-benefit and the TCO of different mobility types to other objective functions such as LCOH, GWP and Risk. This is necessary because demand and infrastructure are closely affecting each other, and the TCO is a relevant metric from the user point of view, while the SCB one is key for decision-making at the governmental level where subventions can be implemented. In Table 1, the specific features that support the novelty of our proposal are given and compared with other frameworks.

3. Problem statement and objective

The problem formulation can be stated as follows. Given the hydrogen demand to be used in buses, heavy-duty trucks and industry, the objective is to determine the best HSC from a combination of criteria that considers not only economic and environmental indicators but also social aspects. For this purpose, four criteria are proposed to compare the different outcomes: LCOH, GWP, Safety risk and SCB. To optimise them, production, storage, transportation and distribution constraints need to be satisfied, so a set of techno-economic data is used to solve a supply chain location-allocation model. The objective functions can be solved separately, but the goal is to compare solutions proposed by single-objective optimisations to the multiobjective ones to find the best trade-off solution that ensures sustainability.

The contributions of this paper are:

- The introduction of new optimisation criteria – Total Cost of Ownership and Social Cost-Benefit – into the mathematical model. To the best of our knowledge, this is the first HSC model that includes the TCO of vehicles and the SCB in the optimisation phase.
- The application of the methodology and model (presented in Sections 4 and 5) to the "Green H_2 in Hungary" project with three scenarios for Hungary that explore several factors (i.e., demand volume and type, production technology type). The research framework of the study is presented in Fig. 1. The *input* block corresponds to all the databases, hypotheses and scenarios chosen by the project team. The integration of the mathematical model and the multiobjective optimisation approach constitutes the core of the approach. The snapshots and the results concerning the decision variables and objective functions are the main *outputs*.

4. Methodology

The optimisation approach of HSC proposed by [33] has been adapted to Hungary to answer the following questions:

- what is the best option for production and storage of hydrogen in Hungary?
- is centralised or decentralised production more cost-effective?
- is it possible to find competitive targets for a national scale (without imports)?
- what is the environmental impact of different HSC options for Hungary?
- what is the safest configuration of the HSC in Hungary?
- what is the impact of the economies of scale and market in the Hungarian HSC?
- when will the total cost of ownership of fuel cell buses and trucks be competitive with diesel technology?
- which approach is more efficient, single- or multiobjective optimisation?

4.1. Supply chain network

This work focuses on the HSC design for Hungary, considering five echelons, i.e., energy sources, production, storage, transport and market (Fig. 2). Five time periods are considered (2030–2050) with a time step of 5 years because Hungary considers the period 2021–30 as a preparation and preliminary period for H_2 technologies with a focus on

Table 1
Modelling details of previously developed frameworks using SCB compared with our proposal.

Publication	SCB analysis	TCO included	Mobility	Industry	Disaggregated demand	SCB Excel calculation	Optimisation model	SCB[a] optimised	TCO optimised	Comments
Creti et al. [85]	X	X	X		X	X				Cost-benefit analysis
Cantuarias-Villessuzanne et al. [38]	X	X	X		X	X				SCB
Dayhim et al. [36]	X[a]		X				X	X[a]		[a] Total Daily Social Cost
Talebian et al. [37]	X[a]		X				X	X[a]		[a] Social carbon cost
Ruf et al. [18,86]		X	X		X	X[b]				[b] Assumption
Ochoa Robles et al. [26]	X	X	X		X	X	X			Total daily cost optimisation
Shamsi et al. [87]	X[a]		X			X	X			[a] Total cost analysis and total benefits analysis
Our proposal	X	X	X	X	X[c]	X[d]	X	X	X	[c] Disaggregated demand for mobility and aggregated for industry[d] only for validation purposes. SCB and TCO are optimised

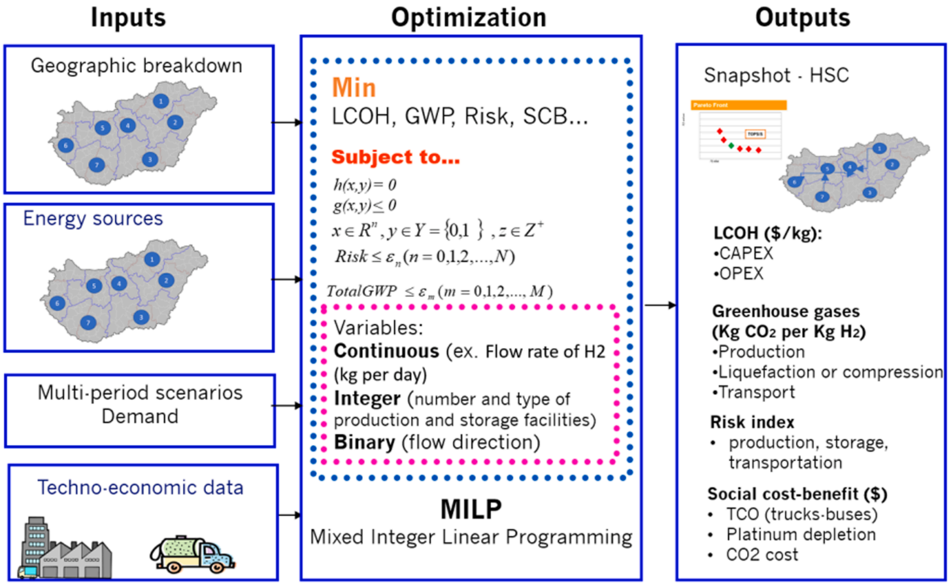


Fig. 1. Methodological framework.

fundamental and applied research [14].

4.2. Data collection

A considerable amount of data was collected for this study. The territorial breakdown considered the internal regions for the discretisation, and a deterministic demand for each region is assumed. The data set includes information related to the hydrogen demand and technical, environmental, economic and risk data associated with each component of the HSC. Information on the purchase and maintenance expenditures for trucks and buses is also included. Some data was collected from recent data and publications (REKK, NECP, IEA, FCH JU, H2 Observatory [52], IRENA, etc.) and from interviews with experts in the energy region and professors (researchers specialized in the energy field and sociologists); however, since the technology is evolving and the market is not yet well defined, there is a high degree of uncertainty on many inputs, the sensitivity of some of them will be investigated with a special focus on demand analysis.

4.2.1. Techno-economic data

All the techno-economic parameters (i.e., minimum and maximum production and storage capacities, average delivery distance between locations and capacity of each transportation mode, etc.) are defined in Appendix A. In this section, we present only the main specific issues linked to Hungary.

4.2.2. Geographical breakdown

According to its geographic and administrative segmentation, Hungary is divided into regions, representing 7 zones (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 Hungarian Central Statistical Office (*Központi Statisztikai Hivatal* - KSH).

4.2.3. Energy sources and production facilities.

The projected availability of renewable and fossil energy sources included in this study uses the latest modelling results for Hungarian National Clean Development Strategy by REKK, 2021. Table 2 presents

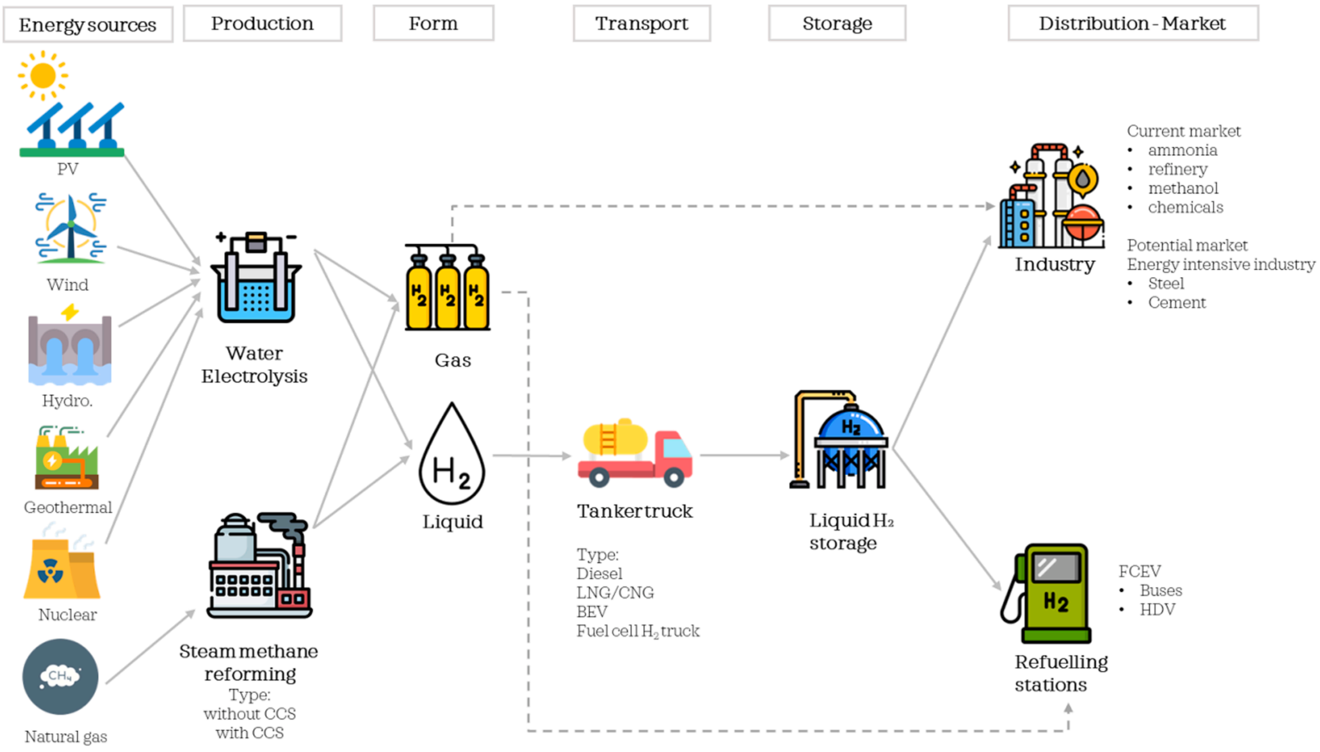
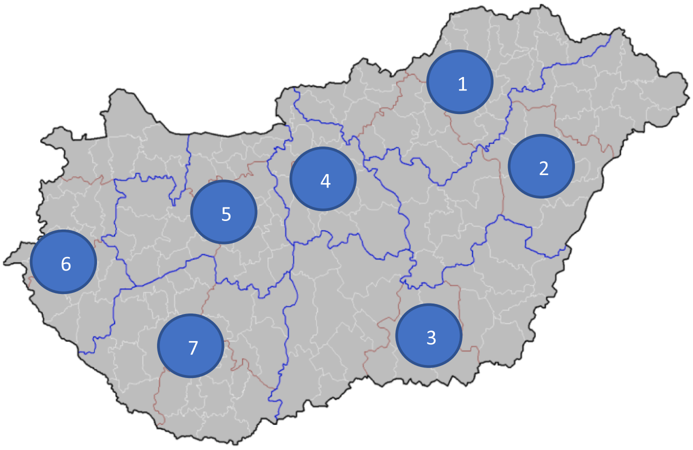


Fig. 2. The Hydrogen Supply Chain. Icons from https://www.flaticon.com/.



g	Name of the region	Regional centre
1	Northern Hungary (Észak-Magyarország)	Miskolc
2	Northern Great Plain (Észak-Alföld)	Debrecen
3	Southern Great Plain (Dél-Alföld)	Szeged
4	Central Hungary (Közép-Magyarország)	Budapest
5	Central Transdanubia (Közép-Dunántúl)	Székesfehérvár
6	Western Transdanubia (Nyugat-Dunántúl)	Győr
7	Southern Transdanubia (Dél-Dunántúl)	Pécs

Fig. 3. Geographical breakdown of Hungary. Adapted from: https://www.mapsof.net/hungary/hungary-admin-divisions.

the strategic objectives for the development of renewable energy from 2020 with a clear trend to completely remove fossil fuels from the energy mix from 2045. The zones with potential development of RES are taken from the Hungarian Energy and Public Utility Regulatory Authority (MEKH) [88–89]. 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 2030 to 2050 is projected.

Two production types are considered, i.e., alkaline water electrolysis and SMR with and without Carbon Capture and Sequestration (CCS). The high potential of renewable energy (solar, wind, geothermal, …) and nuclear power in the country makes electrolysis a key option for green hydrogen production. Large scale electrolysers for the industry are currently in demonstration phase [17], but by 2030, it is assumed that 1 MW, 20 MW and 100 MW electrolysers will be commercially available in Europe [51]. However, the commercial production technology used today is mainly based on SMR, so the comparison of this production technology with electrolysis seems to be relevant because of the technology's maturity and scale potential. Although Hungary has limited readiness for wide-scale deployment of CCS, this option has been included because there are plans in place to use CCS technologies by 2030 [28], and a stimulating regulatory environment and support system will also be established [27].

4.2.4. Conditioning, storage and transportation

Distribution today usually relies on trucks carrying hydrogen either as a gas or as a liquid, and this is likely to remain the main distribution mechanism over the next decade [25]. Highly-insulated cryogenic tanker trucks can carry up to 4000 kg of liquefied hydrogen (LH_2) and are commonly used today for long journeys of up to 4000 km [25]. However, pipelines are likely to be the most cost-effective long-term choice for local hydrogen distribution if there is sufficiently large,

Table 2
Electricity production capacity. Results from “Modelling results for Hungarian National Clean Development Strategy Source” (REKK, 2021).

GWh per year	2020	2025	2030	2035	2040	2045	2050
Nuclear[1]	14,892	14,892	33,814	22,645	18,922	18,922	18,922
Coal	3951	2637	276	40	0	0	0
Oil	95	0	0	0	0	0	0
Natural gas	4193	4428	3148	1411	853	0	0
Biomass	1874	1826	1494	2248	7271	11,076	10,861
Hydro power plant	244	244	244	244	244	244	244
Wind	743	743	1496	1948	1506	1506	21,983
Solar	1875	6000	10,874	13,620	14,911	29,901	56,074
Geothermal	20	20	779	779	779	1885	2254
Total (GWh)	27,886	30,790	52,125	42,935	44,488	63,535	110,336
RES (%)	17 %	29 %	29 %	44 %	56 %	70 %	83 %
RES + Nuclear (%)	70 %	77 %	93 %	97 %	98 %	100 %	100 %

[1] The current nuclear plant is Paks on the Danube to the south. In the current plan it is expected to be decommissioned by 2030 because it was built in the 70s and it is already at the end of its lifecycle. However, two new nuclear power plant units are expected to be built in Hungary by 2030, each with a capacity of 1200 MW (Paks2) [12].

sustained and localised demand. The currently operating natural gas pipelines should although be technically adapted to hydrogen distribution. Some analyses to evaluate the pipeline distribution at a European level are under development (e.g. REKK EGMM and REKK Hydrogen Infrastructure model [90]). This study focuses only on the conditioning, storage and distribution of LH_2 that is considered instead of compressed gaseous hydrogen because LH_2 has a high energy density, and it is easier to handle, transport and store.

Hydrogen can be stored above ground and underground [17]. Further research is needed to assess what storage type is likely to be needed in the future in terms of volume, duration, price, and speed of discharge and to examine development options [25]: geological storage is the best option for large-scale and long-term storage, while tanks are more suitable for short-term and small-scale storage but there are ongoing efforts to reduce the size of the tanks [25]. Tanks storing compressed or liquefied hydrogen have high discharge rates and efficiencies of around 99 %, making them appropriate for smaller-scale applications where a local stock of fuel or feedstock needs to be readily available [25]. In this study, only tanks for storing LH_2 are considered.

4.2.5. *Distribution to final consumer*

The final echelon in the HSC is the distribution of LH_2. It can be delivered to industry or refuelling stations. Our previous model only computed the number of fuelling stations to be installed [39]. In this model, the refuelling stations are integer variables to be optimised based on capacity-demand constraints. Parameters related to refuelling stations are reported in Appendix A and equations in Appendix B. It is recommended to install refuelling stations at least every 150 km by 2030 for buses, cars and trucks [17]. Currently there is one refuelling station in Hungary [91].

4.2.6. *Demand estimation*

A deterministic demand of hydrogen for industry and FCEV is considered. Hungary has a significant potential for hydrogen use in industry [28]. Industrial sectors included in the model are: ammonia production, refining, petrochemical (olefins and aromatics production), steelmaking (H_2-based direct reduced iron) [13] and cement [27,52]. The daily demand for industry is summarised in Fig. 4.

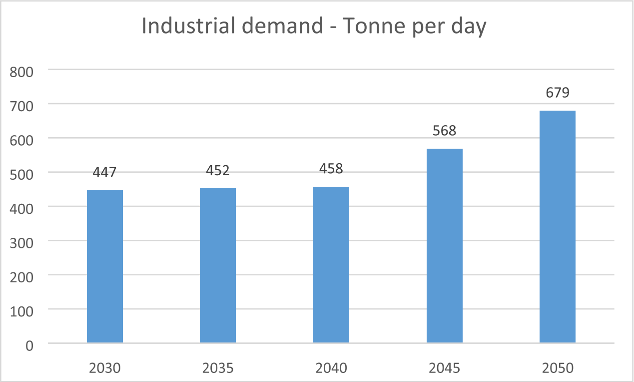


Fig. 4. Industrial demand per period (Tonne per day). Calculations using data from [27].

The Hungarian National Hydrogen Strategy [27] highlighted that for the transportation sector, one main objective is to gradually reduce fossil fuel use with a focus on heavy-duty vehicle traffic (with its corresponding reduction of the carbon footprint). For this reason, this study excludes the demand of private cars to measure if a market considering only HDVs would be large enough to guarantee low hydrogen fuel costs. For the case of FCHDTs, trucks above 12 tonnes for long-distance freight (international and national logistics) have been considered, and the data has been taken from the HU-TIMES model [18]. Data for 4x2 tractor (+trailer) of 40 tonnes gross vehicle weight [86] have been used to calculate the TCO with an annual mileage of 110,000 km per FC HDV for Hungary (HU-TIMES model).

Hydrogen demand for buses has also been included as currently in the HU-TIMES model. Both short- and long-distance buses have been taken into account, and an annual mileage of 60,000 km per bus is assumed (HU-TIMES model). The database and references can be found in Appendix A.

The mobility demand values are indicated in Fig. 5, as well as the projected demand for mobility from Hungary’s National Strategy, which includes not only HDVs but also private cars, trains, ships. However, this scenario was not tested because beyond 2030, the data for the specific number of buses and HD was not available. It must be yet emphasized that the projection shows that the market for cars can also be very relevant in the SC design and could be included in the future.

The potential demand for hydrogen for mobility is calculated according to Eq. (1):

$$D_{ig}^{T} = FE \times d \times Qc_{g} \tag{1}$$

where the total demand in each district ($D_{i\,g}^{T}$) 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). FE for buses was assumed to be 8.6 kg H_2/100 km [92] and for HD trucks 7.6 kg H_2/100 km (4x2_Trac 330 kW) [86].

4.2.7. *Scenarios*

Hungary’s National Hydrogen Strategy [27], the HU-TIMES model and the Hungarian NECP [12] have been used as key references for scenario definition. To test the impact of demand volume (economies of scale), three scenarios are proposed (Table 3). The first one, “Base Case”

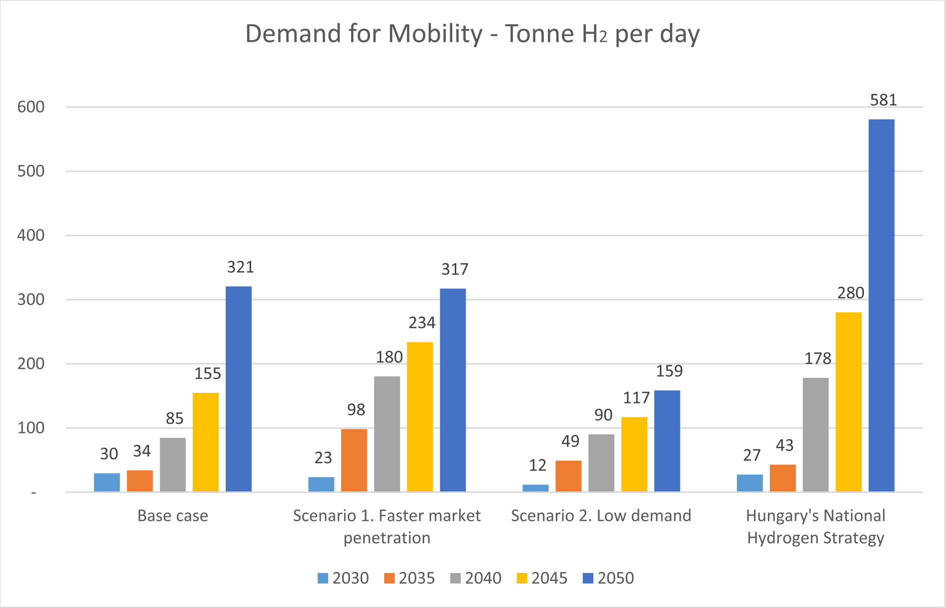


Fig. 5. Buses and trucks demand per period (Tonne per day). Calculations using data from HU-TIMES model and [27].

Table 3
Scenarios' summary.

Base case	**Scenario 1.**Fast market penetration	**Scenario 2.**Low demand
Main reference: HU-TIMES Market 1: • Industry • Mobility (only buses[2]) Market 2 • Mobility (only buses) Technology: • SMR (with or w/o CCS) and electrolysis • Only electrolysis	Market penetration % proposed[1] Market 1: • Industry • Mobility (buses and HD trucks) Market 2: • Mobility (buses and HD trucks) Technology: • SMR (with or w/o CCS) and electrolysis • Only electrolysis	Reference: Scenario 1 (demand halved) Market 1: • Industry • Mobility (buses and HD trucks) Market 2: • Mobility (buses and HD trucks) Technology: • SMR (with or w/o CCS) and electrolysis • Only electrolysis

[1] Bus: 2030 6%, 2035 12%, 2040 18%, 2045 21%, 2050 25%.
HD: 2030 2%, 2035 10%, 2040 18%, 2045 21%, 2050 25%.
[2] FC HD trucks were not included in the HU-TIMES model at the time of the data collections for this study (Nov. 2021).

(BC) has been defined based on data from the HU-TIMES model. Scenario 1 (S1) projects a fast market penetration for both buses and trucks. Scenario 2 (S2) is similar to S1 but with halved demand. Two market types have been tested for each scenario: Market 1 (M1) with industrial demand and Market 2 (M2) without industrial demand. Finally, different technology options to produce grey, blue (SMR, SMR with CCS) or green[3] H_2 (electrolysis) are explored. The details are displayed in Table 3.

4.2.8. Assumptions

The study is based on the following assumptions:

- 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;
- a 10-day LH_2 safety stock is considered;
- the safety risk index is calculated by the methodology proposed by Kim et al., [35];
- the number of plants is initialized at a null value when only electrolysis is allowed. In the scenarios including SMR, the H_2 plants that exist are supposed to be available to supply both industrial and mobility demand. A few plants have been identified based on the REKK database (Fig. 9- base map);
- the cost of migrating a current refuelling station to H_2 fuel is not considered;
- the learning rate cost reductions due to the accumulated experience is considered as 2 % per period [93];
- For the TCO calculation, neither subventions, tax and road roll exemptions, nor public revenues are taken into account to mitigate the technology migration. Support for infrastructure is also not considered because, currently there are no specific national carbon taxes or fiscal rules in Hungary that would promote the use of renewable or low-carbon hydrogen [28].

5. Mathematical model

The model formulation based on MILP takes into account the reference models [35,39,45–46] to develop the equations for production, storage and transportation. However, new equations have been added due to the inclusion of new objective functions. 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 plant

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[3] In this work, "green H_2" is considered when produced by using RES or nuclear power, and electrolysis. However, in recent studies, H_2 produced from nuclear power is called "pink H_2".

of size *j* involving different production technologies *p*, stored in a storage unit *s* and distributed by a transportation mode *l* that uses fuel *f* from one district *g* to another *g'* (with $g' \neq g$), to be used in a market *v* in the time period *t* for a multiperiod approach (Fig. 2).

A specific feature of this updated model is the introduction of the number of refuelling stations as an integer variable. Another modification is the calculation of the LCOH instead of the Total Daily Cost used in [39], which did not report the present values and strongly depended on the capital change factor (years) having an important impact on the cost results as explained in our previous sensitivity analysis [94]. In this version, the constraints related to the Total Cost of Ownership for HD vehicles and buses as well as other constraints related to the Social Cost-Benefit function have been included.

Sections 5.1.1-5.1.3 and 5.2.1 formulate the four objective functions to be used in the optimisation strategy (Fig. 6). The full mathematical model can be found in Appendix B.

5.1. Single-objective functions

5.1.1. Levelized cost of hydrogen

The Levelized Cost of Energy (LCOE) is a well-established metric to compare the generation costs of electricity today, considering rapidly changing power systems [95]. Although this metric is similar to a discounted average cost, it better represents a regulated market. However, by adjusting the discount rate for the implicit cost of price volatility, the LCOE concept also apply, in principle, in the context of deregulated markets [95].

The Levelized Cost of Hydrogen (LCOH) is based on the same principle and is a widely used tool for modelling, policy-making and public debate [49–52]. The LCOH (in \$/kg) is derived by dividing the discounted total costs by the sum of hydrogen produced over the economic lifetime of assets [49]. Due to the multiperiod nature of our HSC optimisation model, the LCOH during time period *t* (Eq. (2)) is given as a sum of two terms in the numerator, the first one related to the CAPEX where the facility capital cost at time *t* (FCC_t) [including production plants, storage facilities and refuelling stations] and the transportation capital cost at time *t* (TCC_t) are discounted by using a discount rate of *r* = 12 %. In Eq. (2), n_t corresponds to the investment year which can take place every 5 years before the beginning of the period (n_1 starts at year 0, n_2 year 5, n_3 year 10…). Only the capital cost of new plants installed in the time period is counted for each *t,* and it is assumed that the investment is made every 15 years [51] when new facilities are to be reinstalled if the demand requires it. No CAPEX has been directly considered for energy sources (i.e. they have been considered as feedstock through electricity cost). The second term is similar but applied to daily OPEX brought to annual values (α = 365 days) and then discounted, where the facility operating costs at time *t* (FOC_t), the transportation operating costs at time *t* (TOC_t) and the cost of importing energy sources (ESC_t) are included. In this case, nn_t are the years included in each period by considering the whole time-horizon [2030–2050] (i.e., nn_1: years 1–20, nn_2: years 6–25, nn_3: years 10–30, …). The discounted costs are finally divided by the produced hydrogen in a given time period; however, since in the model the production should be equal to the demand, it is valid to use the total demand of hydrogen (deterministic parameter) from *i* in grid *g* and time period *t* (DT_{igt}) to maintain the model linearity. LCOH is reported in \$ per kg H_2 for each time period, and the sum is optimised. An example of this calculation is displayed in Appendix F (LCOH).

$$LCOH_t = \frac{\frac{(FCC_t + TCC_t)}{\sum_{n_t}(1+r)^{n_t}} + \sum_{nn_t}\frac{\alpha(FOC_t + TOC_t + ESC_t)}{(1+r)^{nn_t}}}{\sum_{n2}\frac{\alpha\sum_{i,g}DT_{i,g,t}}{(1+r)^{nn_t}}} \tag{2}$$

5.1.2. Global warming potential

The total GWP (g CO_2-eq per day) is calculated by the sum of the GWP for production, storage and transportation as proposed in [33]:

$$GWPTot = \sum_t (PGWP_t + SGWP_t + TGWP_t) \tag{3}$$

5.1.3. Relative safety risk

The wider adoption of hydrogen requires that safety and risk issues be rigorously investigated. Yet, it must be emphasized that risk assessment of new hydrogen production and storage technologies is an area of great interest but for which there is still little feedback. It is admitted that quantitative risk assessment (QRA) through modelling and simulation of fire and explosion risk of hydrogen is an important tool for enabling safe deployment of hydrogen that can be used to properly quantify these risks. Yet QRA requires reliability data, and currently hydrogen QRA is limited by the lack of hydrogen specific reliability data, thereby hindering the development of necessary safety codes and standards [9–10]. In this model the total relative safety risk (units) is calculated by the sum of the relative risks for production, storage and transportation as proposed in [33,35]:

$$TR_t = \sum_t (TPRisk_t + TSRisk_t + TTRisk_t) \tag{4}$$

5.2. Multiobjective optimisation

5.2.1. Social Cost-Benefit (tri-objective)

The methodology for SCB analysis follows the guidelines developed in [18,26,38,86]. As previously mentioned, one of the main contributions of this paper is the inclusion of this function in the optimisation model and not as an additional post-optimal calculation. In order to adapt the methodology, it was necessary to clearly define the type of technology that could be replaced. Since the case study includes both industry and mobility, it was possible to adapt the methodology to the latter one by comparing current internal combustion buses and trucks using diesel and their equivalence in FCEBs and FCHDTs. For industry, a similar comparison was not possible so far because several industry types are aggregated in the available database.

$$SCB_t = \sum_v (\Delta TCO_{v,t} + \Delta CA_{v,t} + \Delta PD_{v,t}) \tag{5}$$

In Equation (5), the first term corresponds to the net present value of the economic comparison where the Total Cost of Ownership includes the purchase prices, running cost, maintenance, AD Blue, insurance and road toll costs for a vehicle type *v* in period *t*. $\Delta TCO_{v,t}$ is the difference between the buses or trucks using different fuels (diesel vs H_2). The main

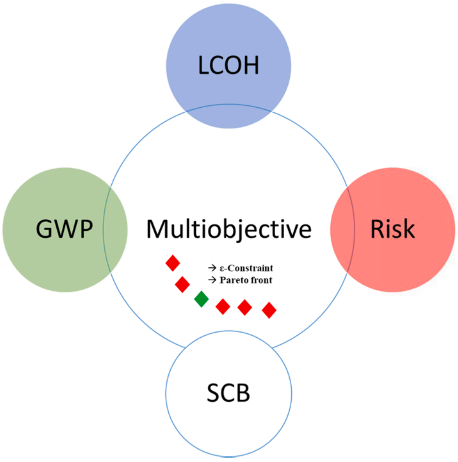

Fig. 6. Objective functions for a sustainable design of a Hydrogen Supply Chain. LCOH: Levelized Cost of Hydrogen; GWP: Global Warming Potential; SCB: Social Cost-Benefit.

advantage of including this function in the optimisation model is that the LCOH will be minimised while optimising the SCB (maximisation function). The fuel price is a key variable affecting the vehicles' running costs. The scenarios assume that the increased cost will be transferred to the end-user [21] (TCO). The use of SCB in the optimisation stage seems to be very relevant since the deployment of hydrogen can be viewed as a chicken and egg strategic problem: the cost and demand of hydrogen are dependent on each other, so a competitive price needs to be ensured and this depends on the whole installed infrastructure.

External costs correspond to net present values for carbon abatement ($\Delta CA_{v,t}$) and platinum depletion for a vehicle type v in time period t ($\Delta PD_{v,t}$). Once again, the integration of all the variables allows quantifying and optimising the GWP for the network, then, when the SCB is maximised, the CO_2 emitted to supply fuels for the mobility market v is minimised. Today, there are uncertainties about the CO_2 pricing mechanisms that will take place for road transportation (e.g., Emissions Trading System (ETS) adaptation). For both internal combustion and fuel cell vehicles, a Well-to-Wheel approach is considered. This ensures that the benefit of zero tank-to-wheel emissions from fuel cell vehicles is accounted for and that the emissions that are part of the HSC (Well-to-Tank) system are also quantified. In summary, with the use of the SCB function three criteria are optimised (SCB, LCOH and GWP) as well as the TCO function in an indirect manner.

The results from this function are reported in $ and can take negative values when the diesel technology is more competitive. More externalities could be added to reduce the gap among technologies, for example, the air pollution and noise costs were also included in an analysis performed for cars at a post-optimal level [26]. In this study, the main objective is to analyse the gaps in several scenarios in the different time periods before proposing the inclusion of additional potential externalities.

5.2.2. *Multiobjective through augmented ε-constraint method (all functions)*

The global multiobjective model can be formulated in a more concise manner as follows:

The objective of this formulation is to find values of the operational $x \in R$, and strategic $y \in Y=\{0,1\}$, $z \in Z+$ 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 expressed as linear functions of the associated decision variables. The solution consists of a Pareto front composed of solutions that represent different possibilities of supply chain configurations.

6. Solution strategy and sensitivity analysis

This MILP problem is treated in GAMS 23.9 and solved by CPLEX 12.9 by using both single- and multiobjective optimisation approaches. Fig. 7 displays the design of experiments for the sensitivity analysis of the scenarios listed in Section 4.2.7, by varying the demand scenarios, the market type and the production technology (SMR, electrolysis or both). A total of 60 experiments are needed if each objective strategy is run separately.

For single-optimisation, LCOH, GWP, and risk are separately optimised. For SCB maximisation, LCOH, and GWP are simultaneously minimised as explained in Section 5.2.1. Finally, the multiobjective optimisation that includes LCOH, GWP, risk and SCB is solved by implementing the augmented ε-constraint (AUGMECON) method as introduced by Mavrotas et al. [96], where all but one objective are converted into constraints and only one objective is to be optimised. The AUGMECON code is available in the GAMS library (https://www.gams.com/modlib/libhtml/epscm.htm). By varying the numerical values of the upper and/or lower bounds, a Pareto front can be obtained. In this work, 21 grid points have been tested and the values for the last optimisation iteration have been selected as the preferred solution from the Pareto optimal options.

7. Results and discussion

The new MILP model incorporating SCB aspects contains 17,380 equations, 9536 continuous variables, and 4340 discrete variables. Single-objective optimisations took from 0.06 to 20 CPU seconds to find a solution with an optimality gap below 0.01 %, depending on the scenario (processor Intel®Core™i7-4790). More precisely, we solved a total of 12 different scenarios that result from the combination of the following factors (1) three scenario types (BC, S1 and S2, (2) two market types (industry and mobility or only mobility), (3), two technology options (SMR and electrolysis or only electrolysis). For comparison purposes, optimal networks for those 12 scenarios were obtained by following 5 optimisation alternatives: LCOH, GWP, risk minimisation; SCB maximisation; and multiobjective optimisation through the ε-constraint method; resulting in a total of 60 experiments (runs). For multiobjective optimisation (using the ε-constraint method) finding the Pareto front and reaching the best trade-off solutions took around 7 h. Due to the large amount of data generated from the different experiments, a summary of the most relevant results is given here with a specific focus on our research questions presented in Section 4. Results for the 12 scenarios by including the 5 optimisation options are summarised in Fig. 8. Detailed results are presented in Appendix C and the statistical analysis to support our conclusions is given in Appendix D.

Minimise {GWP }

Subject to:

$h(x,y)= 0$

$g(x,y)\leq 0$

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

$LCOH \leq \varepsilon_l$ (l=0,1,2,…,L) → min function

$Risk \leq \varepsilon_n$ (n=0,1,2,…,N) → min function

$SCB \geq \varepsilon_m$ (m=0,1,2,…,M) → max function

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

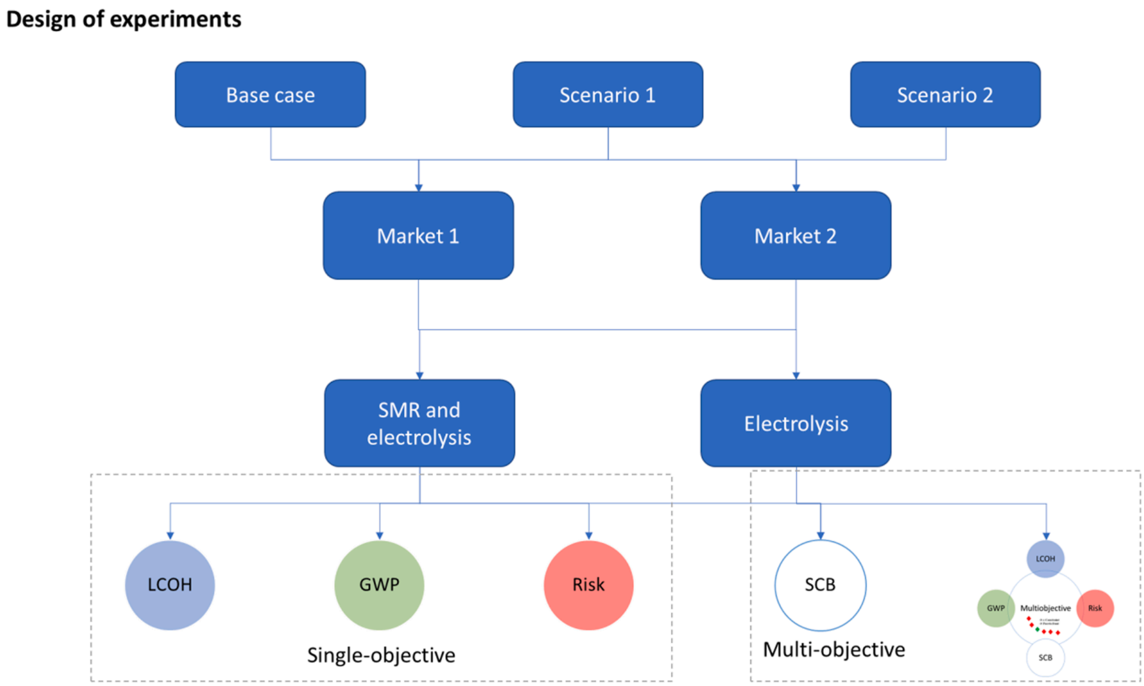

Fig. 7. Design of experiments for sensitivity analysis. LCOH: Levelized Cost of Hydrogen; GWP: Global Warming Potential; SCB: Social Cost-Benefit.

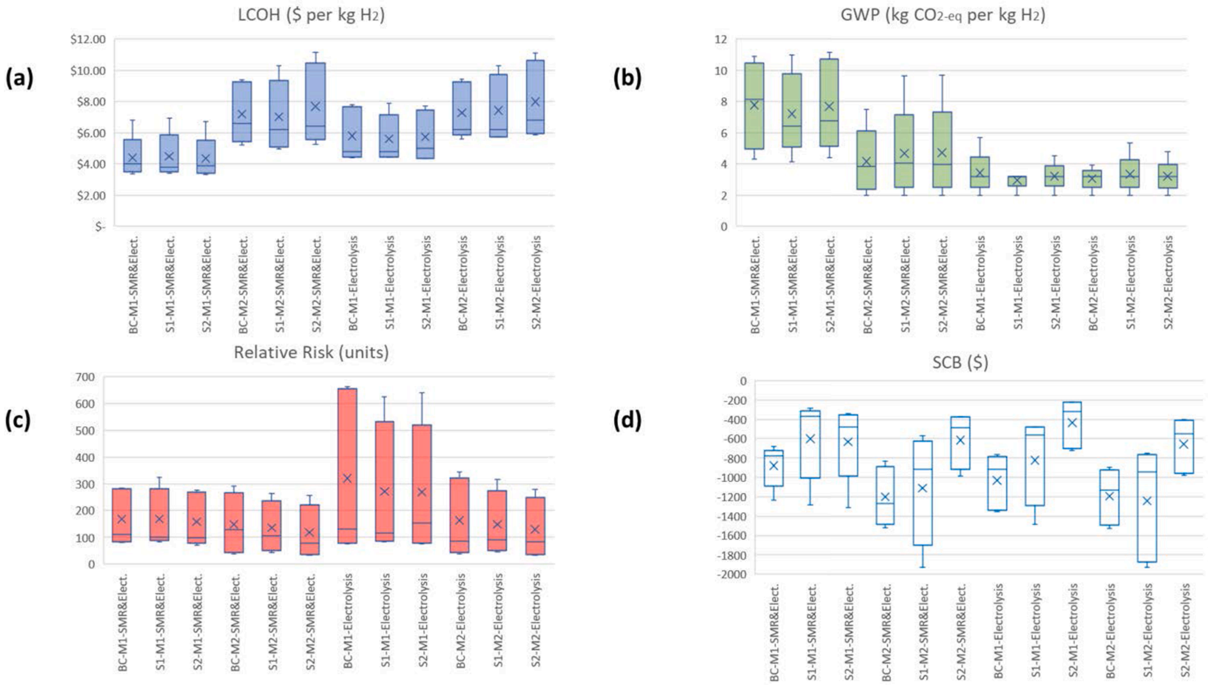

Fig. 8. Results summary for all the scenario combinations from the design of experiments.

7.1. LCOH

Configurations with an average LCOH for the time horizon from 2030 to 2050 range from \$3.34 to \$11.15 per kg H_2 (Fig. 8a). Based on the P-values (Appendix D), LCOH has a significant relationship to the market type, followed by the technology type, and in the last place (still significant) with the demand volume. By comparing the technologies, lower average LCOH values are obtained in experiments for M1-SMR&electrolysis (i.e., \$4.41 per kg H_2) compared to the M1-Electrolysis option to produce green hydrogen (\$5.71 per kg H_2). This is in accordance with some reports where a combination of electrolysis and SMR production is expected in practice [14]. The scenarios where only halved mobility demand is included (M2) resulted in a higher LCOH independently of the technology used or the demand volume because the current installed capacity cannot be used for mobility demand, and new investments need to be done. The technology used with M2 has a low impact on the average cost (M2-SMR&electrolysis: \$7.29 vs M2-Electrolysis: \$7.57 per kg H_2) and the demand volume has a minimal effect. The lowest costs resulted from the minimisation of LCOH followed by SCB, multiobjective and risk optimisations (see the specific

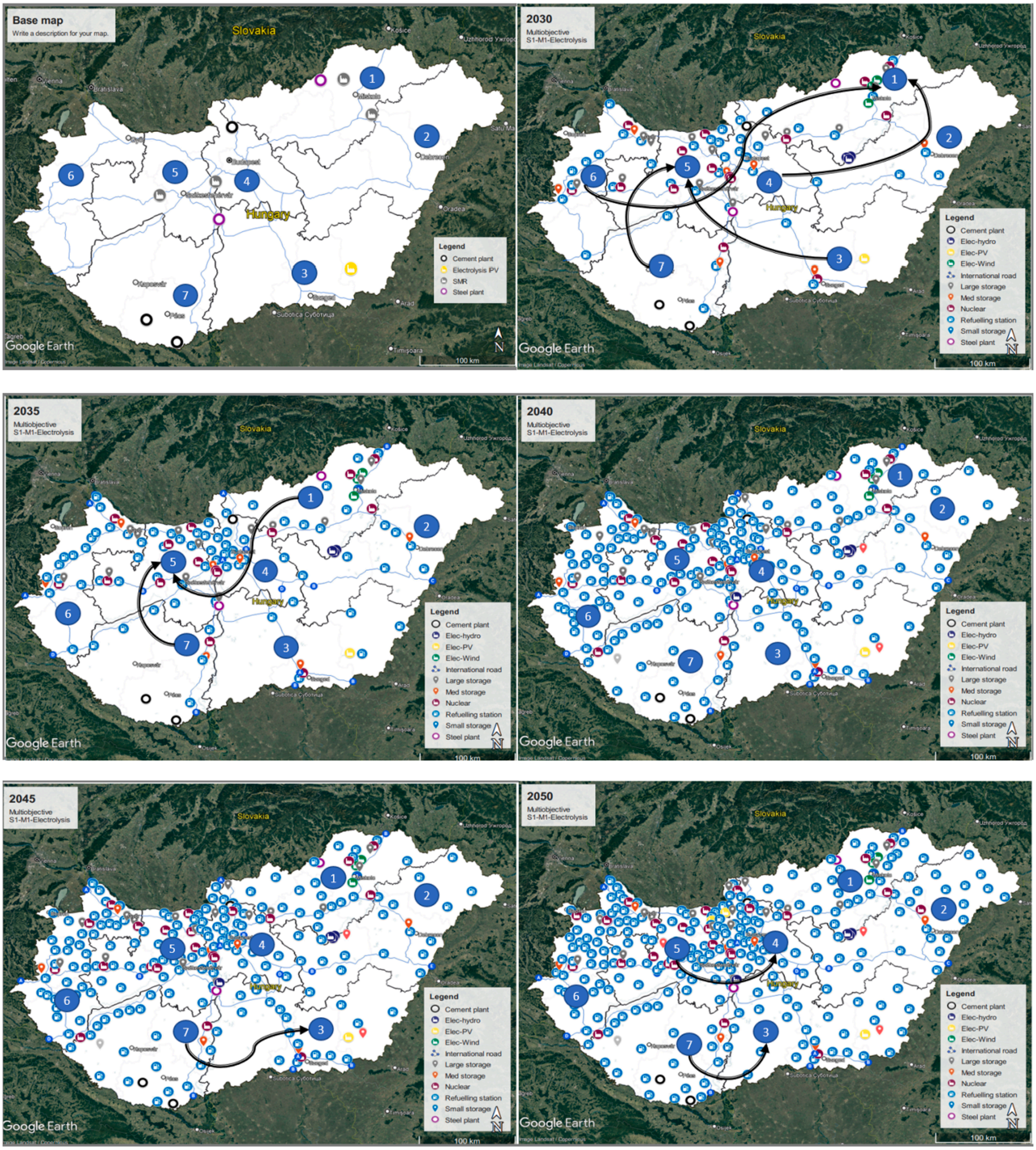

Fig. 9. Green hydrogen supply chain for scenario 1 solved by multiobjective optimisation (2030–2050). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

results for each criterion in Appendix C1-C4). The GWP minimisation resulted in the highest LCOH, thus reflecting the antagonist nature of these two criteria. From the three demand volume scenarios (BC, S1 and S2), results display a similar trend with higher variation among them for M2 options (Appendix C3-C4).

7.2. GWP

In Fig. 8b, the global results for GWP indicate the lowest and highest values as 1.98 and 11.13 kg CO_2-eq per kg H_2, respectively. For this target, the main factor is the technology type (Table D1), with considerably lower values for all scenarios using electrolysis exclusively to produce green H_2. Results for S1-M1-Electrolysis have as minimum and maximum emissions 1.98–3.21 kg CO_2-eq per kg H_2, which are always lower compared to experiments with S1-M1-SMR&Electrolysis (4.15 to 10.99 kg CO_2-eq per kg H_2). It is, however, important to highlight that optimal HSC solutions for this criterion select electrolysis using nuclear source as the preferred option (based on availability), followed by wind (based on the CO_2-eq emissions), while solar and geothermal power are chosen sporadically. This is an important finding because Hungary is developing the solar power sector so if PV is the only/more important source for H_2 production in the future, this would need to be adjusted in the model. These results reinforce the importance of the definition of the initial scenarios for optimisation studies. The second important factor is the market type: higher emissions are found for M1 scenarios. By comparing the P-values for the demand volume (BC, S1 and S2), it is possible to conclude that this factor is not significant in the optimisation of the GWP, so the economies of scale are not affecting this target if evaluated alone. The lowest GWP values obtained from the single-objective minimisation of GWP are followed by the multiobjective and SCB optimisations. The risk and the LCOH optimisations resulted in higher values for GWP (Appendix C5-C8).

7.3. Risk

The safety risk results (Fig. 8c) are sensitive to (1) technology (type, size and number of installed facilities), (2) market type and (3) demand volume (low significance), see Table D1. The risk is measured by using the relative risk index with average values ranging from 33 to 663 units. Configurations with more transport units (higher flow rates) and more storage/production units are penalised by minimising the relative risk. From Fig. 8c, it can be observed that configurations including "SMR&electrolysis" are preferred options for risk minimisation. Appendices C9-C12 present the differences of the risk index results of SCB and LCOH optimisations resulting in higher values for the relative risk since the best results are obtained for risk, GWP and multiobjective optimisations. However, there is some antagonism between the LCOH-SCB and the risk optimisations. An example is that for the S1-M1-SMR&electrolysis in SCB maximisation vs risk minimisation, the number of storage facilities and transport units varies significantly, i.e., 749 storage units and 132 tanker trucks for the whole-time horizon for SCB vs 103 store tanks and 11 trucks in the risk minimisation. This trend is shared for M1 and M2; however, M1 using "Electrolysis", resulted in the descentralised configurations with the highest risk because many electrolysers need to be installed to cover the demand for industry and mobility (each production unit is penalised). From these results, it can be confirmed that the risk function plays an important role in the design of the HSC network because it influences the centralisation degree as previously reported in [34].

7.4. SCB

The last objective to be analysed is the Social Cost-Benefit. Fig. 8d and Table D1 show that the most important variation is found when the demand volume is different (i.e., BC, S1 or S2). This makes sense because the SCB function in the current model evaluated this aspect only for mobility, where the base case includes only buses and, S1 and S2 include both buses and heavy-duty trucks. The second important factor is the market type, and the production technology is not significant. The SCB is a maximisation function, and for the studied scenarios, no positive values were found from any of the experiments. However, values closer to 0 are found for S2 because the number of vehicles is lower in that scenario. As previously explained in Section 4.2.8, in the SCB function used in this model, neither subvention nor tax exemption has been included in order to analyse first a case when only the TCO, carbon price and platinum depletion are compared for diesel buses and trucks vs FCVs. Globally, values range from -M\$1,930.05 to -M\$224.90 if the diesel vehicles are substituted by FCVs. In Appendices C13-C16, the best values are displayed for the SCB and LCOH optimisations, followed by the multiobjective, risk and GWP ones. Although the optimisation of SCB is giving relatively good solutions for LCOH and GWP, the impact is higher for LCOH which is used to calculate the TCO.

Even if the TCO is lower for diesel vehicles over the time horizon (Table 4), it becomes closer to the TCO of FC trucks from 2035 when the SCB is maximised, and the used technology is SMR&electrolysis. The TCO study from Ruf et al. [18] exhibited a clear trend toward the cost competitiveness of FCHDT technology (no additional comparisons can be done with other studies that include SCB calculations [26,38,85] because the application is mobility but for private vehicles). For scenarios where only electrolysis is allowed, there are closer results from 2040. The TCO gap of buses is larger, and it is mainly affected by the difference in the purchase prices as reported in Appendix A.

7.5. Single vs multiobjective optimisation

In this work, single-objective (LCOH, GWP and Risk) and multi-objective (SCB, multiobjective through ε-constraint method) optimisations have been run. The single objective approaches have displayed similar features as those reported in previous works [33–34]. For the multiobjective strategy using ε-constraint, the creation of the Pareto front required around 7 h to obtain the best trade-off solution using the same weight for the 4 criteria. The SCB maximisation includes the LCOH and the GWP, and a few seconds are needed to find an optimal configuration with a trade-off and good results are given for LCOH and GWP. At this point, these multiobjective approaches are complementary because they measure different aspects.

7.6. Snapshot of a sustainable HSC for Hungary

The results of the S1-M1-Electrolysis by using the ε-constraint method in the optimisation are used to illustrate the HSC detailed results. In Fig. 9, an approximation of the network is displayed starting from a base map where current installations are placed (REKK). The black lines are used to separate the regions, and the blue lines are the International Road Network (E-roads). Facilities identified in 2021 (base map) are located just to display some industrial demand sites. New facilities are producing hydrogen through electrolysis using nuclear electricity (directly or from the grid) from 2030 to 2050 and wind, solar and hydro power are also present at a lower share. This is in agreement with the discussion presented in [14], which specifies that although some green H_2 capacity will be installed, the higher share expected after 2030 will be based on nuclear energy and RES. To cover industrial and mobility demand in 2030, around 10,500 GWh per year would be needed to produce H_2 via electrolysis. This amount is high compared to the results from other studies [14,27–28] and requires an important share from nuclear power and not only renewables. In the latest results from the Hungarian National Clean Development Strategy (Table 2), it is estimated that Hungary will have a solar PV generation of over 10,874

Table 4
Total Cost of Ownership: comparison for buses and trucks using Diesel or hydrogen.

TCO (\$ per vehicle)						
	Fuel	2030	2035	2040	2045	2050
Bus	Diesel	\$ 595,844	\$ 381,597	\$ 258,323	\$ 212,002	\$ 170,959
	H_2 – SCB max – S1-M1-SMR&Electrolysis	\$ 961,052	\$ 532,639	\$ 347,499	\$ 315,865	\$ 234,644
	H_2 – SCB max S1-M1-Electrolysis	\$ 1,018,947	\$ 567,500	\$ 377,361	\$ 331,344	\$ 250,002
Truck	Diesel	\$ 643,537	\$ 476,962	\$ 334,376	\$ 245,220	\$ 207,246
	H_2 – SCB max S1-M1-SMR&Electrolysis	\$ 781,428	\$ 480,447	\$ 342,176	\$ 291,868	\$ 209,760
	H_2 – SCB max S1-M1-Electrolysis	\$ 875,226	\$ 536,926	\$ 390,559	\$ 316,946	\$ 234,642

GWh per year in 2030 and 1496 GWh per year for wind power. Solar PV could cover the whole H_2 demand projected in this study for 2030; however, the LCOE and CO_2 emissions values for the solar PV are penalising this technology in optimisations. This point requires particular attention in terms of the scenarios definition, because even if the use of nuclear and wind power is chosen in the optimisation, in the European roadmaps PV and wind parks are supposed to be coupled with H_2 to increase the flexibility of the energy systems. It is highlighted that although wind power has lower GWP (984 g CO_2-eq/kg H_2) compared to nuclear (2150), the model results reflect the capability constraints present in Hungary for wind-power development that is limited by a strict regulation which only allows wind turbine installations within the 12 km range of populated areas [97]. In Table 2, the slow development of wind power in Hungary from 2025 to 2045 is displayed. This fact can also affect the LCOE for wind, as displayed in (Appendix A -Table A.8). In addition, even though solar power capacity will be developed in Hungary in the following years, both LCOE and CO_2 emissions for this technology are higher than the values for nuclear power, so "electricity-PV" is penalised. For these reasons, "electrolysis-nuclear" seems to be one of the main alternatives to be used for H_2 production in Hungary with the current scenarios. So far, the option to import electricity or hydrogen from neighbour countries has not been explored.

Although the maps in Fig. 9 display arbitrary, approximative locations, the sites were located in the regions based on their potential demand, the availability of energy sources and the E-roads. There are many production sites based on electrolysis around Miskolc in Northern Hungary (Region 1) due to the high demand and current location of ammonia and steel industry, and also in Central Transdanubia (Region 5) where SMR production is available nowadays. Indeed, Hungary is evaluating these regions together with Regions 4 and 7 to establish two new hydrogen valleys by 2030 [27]. The majority of wind production plants are located in Region 1. The refuelling stations are placed next to the E-roads, and in the period of 2030, 44 refuelling stations are needed (20 refuelling stations are projected in the national strategy [27]). The number of refuelling stations and storage centres increases with the time based on the demand growth. In Hungary, this point requires more investigation due to the potential of other storage and transportation options (underground storage and pipelines) [14]. In the maps, the arrows represent the road transportation links, and since there are very few of them, the network is a rather decentralised one.

The detailed results are presented in Table 5, from which it can be highlighted that at a national level, the economic results are very close to the European targets, i.e., the hydrogen cost below 1.8 EUR per kilo by 2030 [~\$2,23] if only the production part is taken into account. A LCOH of \$6.33 in 2030 has resulted from the whole HSC, and the specific production cost is around \$2.7 by using electrolysis. It can be emphasised that the costs of transmission and distribution are significant, and the IEA [25] mentions that it could be three times as large as the cost of hydrogen production; this might explain why the configuration is rather decentralised. With regards to the price of H_2 at the refuelling stations, Ruf et al. [18] report that hydrogen needs to be offered below 6 EUR per kg [~\$6.8], so it is important to consider the taxes and surcharges for H_2 fuel that could represent an additional 113 % according to [86], so that from a LCOH of \$6.33, a price of \$13.48 per kg H_2 in 2030 at the refuelling station is expected and in 2035 LCOH of \$3.97, would result in a price of \$8.47.

Table 5
Detailed results for producing green hydrogen from scenario 1 solved by multiobjective optimisation.

		2030	2035	2040	2045	2050
Total demand	T per year	171,571	200,890	232,821	292,854	363,762
Demand - Industry		163,000	165,000	167,000	207,500	248,000
Demand - Mobility		8571	35,890	65,821	85,355	115,762
Configuration						
Number of total production facilities	Units	22	22	25	29	35
Number of new production facilities		20		3	4	6
Number of total storage facilities		19	19	25	26	29
Number of new total storage facilities		19		6	1	3
Number of refuelling stations		44	78	183	183	247
Number of transport units		13	6		3	3
Objective functions		**2030**	**2035**	**2040**	**2045**	**2050**
Levelized cost of hydrogen	\$ per kg H_2	\$ 6.33	\$ 3.97	\$ 4.56	\$ 5.08	\$ 3.95
Global warming potential	kg CO_2-eq per kg H_2	3.16	3.14	3.13	3.13	3.16
Total safety risk	units	147	92	97	116	134
Social Cost Benefit	Million \$ per period	−469	−434	−629	−848	−445
TCO		**2030**	**2035**	**2040**	**2045**	**2050**
Bus-Diesel	\$ per vehicle	\$ 595,844.31	\$ 381,597.20	\$ 258,323.11	\$212,002.12	\$170,959.35
Bus - H2		\$1,050,643.74	\$ 573,530.80	\$ 392,425.32	\$337,628.90	\$252,261.43
Truck - Diesel		\$ 643,536.60	\$ 476,961.78	\$ 334,375.95	\$245,220.40	\$207,246.27
Truck - H2		\$ 926,579.47	\$ 546,696.90	\$ 414,964.50	\$327,128.43	\$238,302.91
Capital cost		**2030**	**2035**	**2040**	**2045**	**2050**
Plants, storage, refuelling stations capital cost	M\$	\$ 2,708.91	\$ 66.67	\$ 953.48	\$ 308.80	\$ 680.77
Transportation modes capital cost		\$ 16.59	\$ 7.42		\$ 3.98	\$ 3.73
Operating cost						
Plants, storage, refuelling stations operating cost	M\$ per day	\$ 1.84	\$ 2.02	\$ 2.40	\$ 2.78	\$ 3.45
Transportation modes operating cost		\$ 0.01	\$ 0.00		\$ 0.00	\$ 0.00
Primary energy source cost		\$ 0.13	\$ 0.13	\$ 0.16	\$ 0.17	\$ 0.22
GWP		**2030**	**2035**	**2040**	**2045**	**2050**
Production	Tonne CO_2-eq per day	1009.44	1178.21	1360.69	1711.43	2158.52
Storage		467.71	547.63	634.68	798.33	991.62
Transportation		6.38	3.09		0.53	1.11
Risk		**2030**	**2035**	**2040**	**2045**	**2050**
Production	Units	16	16	19	24	30
Storage		55	55	78	84	98
Transportation		75	21		8	5
Social cost benefit		**2030**	**2035**	**2040**	**2045**	**2050**
Delta TCO	M\$ per period	\$ (505.72)	\$ (586.90)	\$ (891.74)	\$ (1,141.87)	\$ (782.28)
CO2 mitigation for mobility	\$ per period	\$ 39.12	\$ 157.53	\$ 266.56	\$ 296.61	\$ 341.45
Platinum depletion	\$ per period	\$ (1.90)	\$ (4.18)	\$ (3.50)	\$ (2.78)	\$ (4.30)

Carbon mitigation with the HSC has average emissions of 2.99 kg CO_2-eq per kg H_2 compared to some HSC configurations reaching emissions of more than 11 kg CO_2-eq per kg H_2. Only by considering the transport market analysed here (buses and trucks), around 84 thousand tonnes of CO_2-eq emissions can be avoided in 2030 if diesel is substituted by hydrogen; this figure is close to the projections presented in the national strategy for all the transportation sectors [27] (130 thousand tons of CO_2 per year). Reductions by 2050 would be around 1.13 million tonnes of CO_2-eq emissions per year, only for the HD transport sector.

8. Conclusions and perspectives

This study tested different criteria for designing a sustainable HSC. The hydrogen supply chain includes energy sources, production and storage facilities, transportation modes and different markets (industry and mobility), and its evolution from 2030 to 2050 has been studied with a multiperiod optimisation. A new MILP model has been proposed to optimise the HSC by considering the inclusion of the SCB criterion in the optimisation stage that can be further used to calculate the total cost of ownership of the mobility market, i.e., buses and heavy-duty vehicles for this study. Both the risk index and SCB function can be considered as specific social criteria in addition to the levelized cost of hydrogen for the economic pillar and the GHG emissions for the environmental contribution. A total of 60 scenarios have been optimised to test the demand and technology sensitivity. The methodology has been applied to the case study of Hungary, considering a national production without imports.

The scenario definition is of utmost importance and has a serious impact on the results. It can be concluded that it is preferred to have a mixed demand (industry and mobility) and a gradual introduction of FCVs and migration to electrolysis technology to ensure a smooth transition, especially in the first periods. The obtained configurations exhibit an average LCOH ranging from \$3.34 to \$11.15 per kg H_2.

In a market including industrial and mobility demand (buses and trucks), green hydrogen can result in an LCOH of \$6.33 per kg H_2 in 2030 by using electrolysis. Taxes and surcharges for H_2 fuel will impact the final price at the refuelling station, and by using our current database, the H_2 price can be twice the LCOH. This can affect the competitiveness of H_2. According to Ruf et al. [18], by 2030, hydrogen needs to be offered below 6€ per kg [~\$6.8], so additional subventions or tax exemptions would be needed for H_2 to be competitive in 2030. In the same scenario (S1-M1-electrolysis), emissions vary from 1.98 to 3.21 kg CO_2-eq per kg H_2. If both electrolysis and SMR are used, the emissions are considerably higher: 4.15 to 10.99 kg CO_2-eq per kg H_2. The optimal configurations for risk imply a low-medium degree of centralisation with few road transportation links. The best option for production according to the multiobjective optimisation approach is electrolysis coupled with nuclear, wind and hydro power in a decentralised network. The demand of electricity from these energy sources increases considerably if a full transition from blue/grey hydrogen to green hydrogen is accelerated. The maximisation of SCB seems to be very relevant since the deployment of hydrogen can be viewed as a chicken and egg strategic problem: the cost and demand of hydrogen are dependent on each other, so a competitive price needs to be ensured, and this depends on the whole installed infrastructure and the sales of FCVs and hydrogen. In the current formulation, the SCB includes the TCO, the platinum depletion and the carbon abatement for buses and trucks. This analysis was not extended to the industrial market due to the lack of detailed data about the final users, but this can be explored in a future study. Although the TCO is lower for diesel vehicles over the time horizon, it becomes closer to the TCO for FC trucks from 2035 on when the SCB is maximised and the technology used is SMR&electrolysis. The TCO gap is larger in the case of buses which can be attributed to the difference in the purchase prices based on the databases used. The inclusion of additional externalities and the reduction of the buses purchase price could help to decrease this gap.

Finally, the results of maximisation of SCB and those of multiobjective optimisation were compared. It can be concluded that these approaches are complementary. The main difference is found in the degree of network centralisation and in the relative risk index with a higher risk for SCB maximisation. The multiobjective optimisation by using the ε-constraint method includes LCOH, GWP, risk and SCB, resulting in a trade-off solution after several calculation hours. Solutions for SCB were found in a few seconds, with trade-off solutions for LCOH and GWP implicitly minimising the TCO. The application of this methodology to additional case studies would allow us to conclude if the results can be generalised but a sensitivity analysis has been developed to analyse the relationship between the objective functions and different factors: market type, technology type and demand volume.

Several research perspectives have been identified, and additional studies could be developed to investigate:

- Energy sources: e.g., Hungary is projecting the development of the solar power sector, biomass is also available. Additional scenarios by including only RES could be developed in the future.
- Other markets: cars, heating, biogas…
- Technology alternatives: PEM vs alkaline electrolysis; pipeline transportation, underground storage, use of hydrogen carriers (e.g., ammonia, liquid organic carriers…)
- SCB function analysis and improvement by including additional catalytic converters' materials (e.g., palladium and rhodium) for automobile industry and other externalities. This might increase the competitiveness of H_2
- Geographical scale: granularity analysis, bottom-up and top-down comparisons, regional analysis (e.g., Visegrad countries), formal GIS analysis, international imports
- Sensitivity analysis: data is frequently updated, meaning demand, facilities lifetime, capacities, CAPEX, purchase prices for vehicles, fuel efficiency, carbon prices and other inputs can require a regular sensitivity analysis
- Additional social aspects that should be taken into account to ensure the HSC sustainability
- The risk assessment could be improved for both, safety, and economic views, by including, e.g., unexpected risks, important for sustainable and resilient supply chains.

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CRediT authorship contribution statement

Sofía De-León Almaraz: Conceptualization, Methodology, Investigation, Software, Formal analysis, Writing – original draft, Visualization. **Viktor Rácz:** Conceptualization, Investigation, Writing – review & editing. **Catherine Azzaro-Pantel:** Conceptualization, Methodology, Software, Writing – review & editing. **Zoltán Oszkár Szántó:** Conceptualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data in Brief - Appendices

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Appendices A-F. Supplementary material

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