Leveraging Renewable Energy for Turkey's Future Hydrogen Supply Chain: A Stochastic Programming Model

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Abstract

Fossil fuel dependence and rising CO_2 emissions due to population growth and technological advancements necessitate a transition to clean energy sources. The transportation sector, a major contributor to CO_2 emissions, requires alternative solutions like hydrogen fuel cell electric vehicles (HFCVs). However, widespread adoption hinges on a reliable hydrogen supply chain (HSC). This study aims to design a HSC for Turkey's transportation sector in 2050, considering potential renewable energy sources. A scenario-based stochastic programming approach is employed to address the uncertainty in demand. Additionally, the Epsilon Constraint Method is used to incorporate multiple objectives, including cost, CO_2 emissions, and risk, into the model. The results show that the types of facilities opened are compatible with the renewable energy potential of each grid and there is a decentralized structure. This study contributes to the design of a sustainable HSC for Turkey, showcasing a methodology that can be adapted by other countries aiming to integrate renewable energy sources into their hydrogen supply chains.

Keywords: Hydrogen supply chain, Renewable Energy, Stochastic programming

I. Introduction

Technology advancements and population growth drive energy use higher, leading to fossil fuel depletion and environmental harm. Reducing carbon emissions, especially in transportation (second to electricity), is a major focus. Battery Electric vehicles help to reduce CO_2 emissions, but limited range and long charging times are drawbacks. Hydrogen fuel cell electric vehicles (HFCV) address these issues with fast refueling (like gasoline) and long range. However, a reliable hydrogen supply infrastructure is crucial for widespread adoption.

The most important points when planning the HSC are determining production locations, supplying raw materials, and delivering hydrogen to the end consumer. Like numerous other countries, research on HSC has been conducted and continues to be conducted in Turkey. Güler, et al. (2021) design a multi-period HSC for Turkey and then turn it into a single-period, multi-objective one (Erdoğan, et al., 2023). In (Erdoğan, et al., 2023), they combine these two studies and make a multi-objective and multi-period HSC plan. Nevertheless, one of the most crucial factors in HSC design in recent times, the green hydrogen production potential, is not addressed in these studies. Generally, coal, natural gas, biomass and a few renewable energy sources are used as primary energy sources (PES) in hydrogen production. However, obtaining the hydrogen obtained through green methods would be the most appropriate way to achieve the first purpose of using hydrogen. Green hydrogen is the type of hydrogen obtained from renewable sources such as wind, solar, hydroelectric, and geothermal. Sgarbossa, et al. (2023) propose an agenda about this topic in their study. A study undertaken by Seo, et al. (2023) focus on developing strategies for delivering hydrogen to customers from offshore production locations, where there is a higher potential for renewable energy. According to Jiang, et al. (2022), renewable energy resources that are overproduced should be converted to hydrogen for storage purposes; they develop an approach for carrying out this.

In this study, an HSC planning that considers renewable energy sources for Turkey is proposed. Although Turkey's renewable energy resources are not at a sufficient level at the moment, the potential is very high and studies on this subject are continuing. Based on this, Dinçer, et al. (2021) published a report revealing the hydrogen production potential in Turkey. We employed this report for our study.

II. Experimental Set-up and Procedure

Erdoğan, et al. (2023) propose the design of HSC in Turkey for 2050. Their model is a multi-objective model that minimizes cost, CO_2 emission and risk. In this study, this model is enriched by including stochasticity to minimize the problems arising from demand uncertainty and by using potential renewable energy resources in Turkey, addressed by (Dinçer, et al., 2021) report. The report indicates for each province how much hydrogen can be produced with potential renewable energy sources after deducting the electricity consumption in the province. To adapt this to our model, these hydrogen quantities are converted into units of primary energy sources. Based on our analysis, we project that the potential outlined in this report can be realized no earlier than 25 years from now.

Therefore, the model is created as a single period model for 2050.

Since HFCV is a new technology, there are uncertainties regarding its demand, hence a scenario-based stochastic programming approach with two stages is used to model this uncertainty. In stochastic programming, there are two kinds of variables. Even if the scenario changes, there will be no change in the values of *discrete control* (i.e., here-and-now) *variables*. They show the choices that need to be made at the beginning of the problem. The decision to open a plant in a grid can be given as an example. Another choice is the amount of hydrogen that will be transported or the amount that will be made in this plant. Their values depend on the scenario. *Continuous dispatch (i.e. wait-and-see) variables* show these kinds of choices. While determining the scenarios, the period between 2020 and 2050 is divided into three 10-year periods, and a total of eight scenarios is created by calculating how much the demand in 2050 would be, depending on whether the demand is high or low during these three periods. In addition, the Epsilon Constraint Method is employed to identify the optimal model that minimizes cost, risk, and CO_2 emissions as in (Erdoğan, et al., 2023).

There are two important points that distinguish this study from other multi-objective stochastic models. The first of these is the inclusion of potential renewable energy resources in Turkey into the model. Secondly, in CO_2 optimization, which is one of the model objectives, in addition to the CO_2 absorption resulting from production and transportation, the CO_2 emission resulting from the production of PES is also calculated as in Equation 1 and included in the objective function of CO_2 optimization. Therefore, the model is empowered to give greater consideration to the utilization of green hydrogen production.

$$TPESCO2_{e,k} = \sum_{p,j,g} PVar_{p,j,g,k} * U_{p,j,e} * PESCO2_{e} \qquad (1)$$

TPESCO2, PVar, U and PESCO2 represent the total CO_2 emissions for each energy source and scenario; the production amount in each facility type, facility size, grid, and scenario; the usage amount of each PES in the facility of type p and size j; the CO2 emissions of each PES in electricity production, respectively.

III. Results and Discussions

The epsion constraint method yields the best solution as the one shown in Table 1.

Table 1. The Objective Results

Total Cost ($/day)	Total CO_2 (kg^{-1}/day)	Total Risk (unit)
103,404,474	34,828,652	3,925

Table 2 shows the number of facilities opened according to plant type and size, and in parantheses, the percentage of these facilities in the total number of plants.

Table 2. Number of facilities opened.

Plant Size/Type	SMR	ELE (Solar)	ELE (Wind)	ELE (Hydroelectric)	H_2S-ELE (Solar)	H_2S-ELE (Wind)	H_2S-ELE (Hydroelectric)
Small	0	118 (37.1%)	109 (34.3%)	20 (6.3%)	5 (1.6%)	12 (3.8%)	6 (1.9%)
Medium	1 (0.3%)	26 (8.2%)	13 (4.1%)	2 (0.6%)	1 (0.3%)	0	1 (0.3%)
Large	3 (0.9%)	1 (0.3 %)	0	0	0	0	0

According to the results, although Turkey's renewable energy resources are sufficient, it is observed that very few (only 1.2%) natural gas-powered SMR production facilities have been opened. This is because the cost of SMR facilities is less than electrolysis facilities and this affects the objective function. The facilities of the ELE, which rely on solar and wind energy, make up a significant share of Turkey's potential renewable energy sources, accounting for nearly 90% of all facilities. This rate also includes H2S-ELE facilities that produce by using sulfur in the Black Sea. It is seen that H2S-ELE facilities constitute approximately 8% of the total facilities.
Fig.1 shows the facilities opened in each grid and the flows between the grids according to the most likely scenario (where demand is low in all three periods).

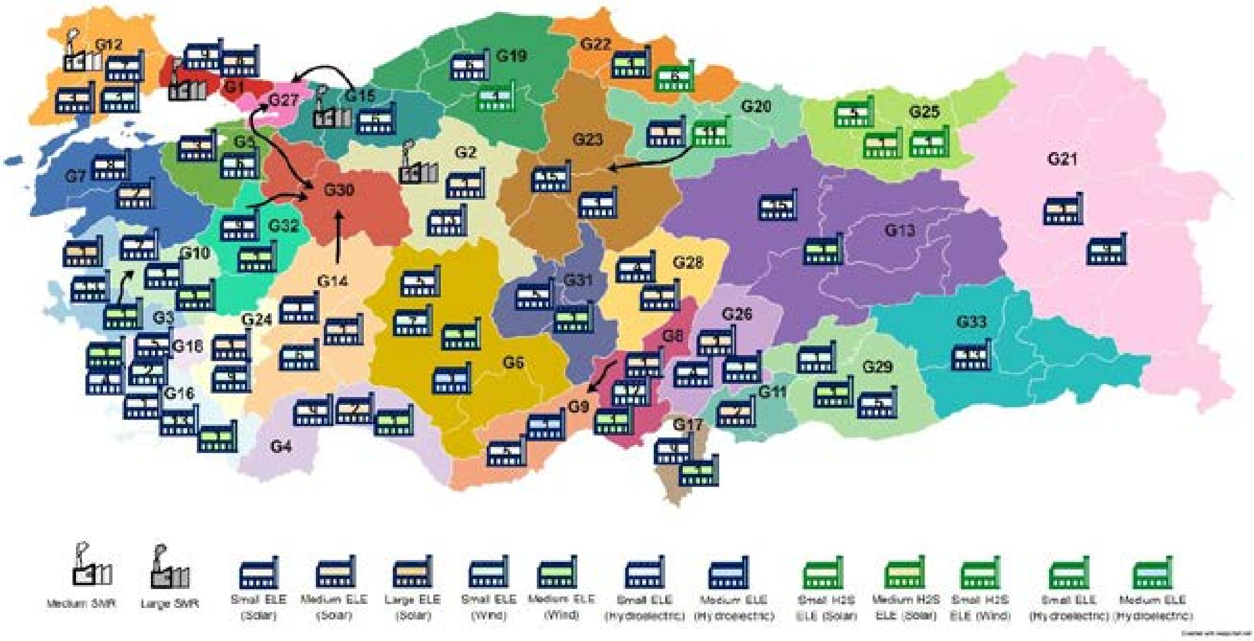

Fig.1: Plants opened in each grid.

It seems that the plant types opened are suitable for the renewable energy potential in the grids. In order to benefit from the sulfur in the Black Sea, H2S-ELE facilities are being opened in the grids on this coast. The network design appears to be decentralized. Plants are opened almost in each grid, usually in small sizes. This is because every grid is rich in renewable energy sources and can meet its own demand. Minimal flow rates between grids contribute to reducing both risk and emissions. Since no facilities have been opened in G30 and G27, the requirements of these grids are fulfilled by the neighboring grids. Moreover, although there are many facilities in G9, G10 and G23, there is also an inflow into these grids. This is because it is more economical to procure from nearby power grids rather than constructing a new plant to fulfill the remaining demand.

IV. Conclusion

In this study, assuming that renewable energy resources in Turkey are used, an HSC is designed for the transportation sector in 2050, which is considered as the earliest year in which this potential can be reached. Since it is impossible to know the hydrogen demand in 2050 in advance, scenario-based stochastic programming is used to control demand uncertainty and the Epsilon Constraint method is used to include all three objectives (i.e. cost, CO_2 emission, risk) in the model. According to the results, the types of plants opened in the grids are compatible with the renewable energy sources of those grids. In addition, since every region of Turkey is very rich in terms of renewable energy resource potential, plants are opened in almost every grid, meaning a decentralized structure is created.

References

Dinçer İbrahim, Javani N. and Karayel G.K, Türkiye için Hidrojen Çiftliği Konsepti Raporu,Report,İstanbul, (2021).

Erdoğan Ahmet and Güler Mehmet Güray, Optimization and analysis of a hydrogen supply chain in terms of cost, CO_2 emissions, and risk: the case of Turkey, International Journal of Hydrogen Energy, 60,48, 22752-22765, (2023).

Erdoğan Ahmet, Geçici Ebru and Güler Mehmet Güray, Design of a future hydrogen supply chain: A multi-objective model for Turkey, International Journal of Hydrogen Energy, 31 ,48, 1775-11789, (2023).

Güler Mehmet Güray, Geçici Ebru and Erdoğan Ahmet, Design of a future hydrogen supply chain: A multi period model for Turkey, International Journal of Hydrogen Energy, 30, 46, 16279-16298, (2021).

Jiang, H., Qi, B., Du, E., Zhang, N., Yang, X., Yang, F., and Wu, Z., Modeling Hydrogen Supply Chain in Renewable Electric Energy System Planning, IEEE Transactions on Industry Applications. 2, 58, 2780–2791, (2022).

Seo, Y., Park, H., Lee, S., Kim, J., and Han, S., Design concepts of hydrogen supply chain to bring consumers offshore green hydrogen, International Journal of Hydrogen Energy, 40, 48, 15126–15142, (2023).

Sgarbossa, F., Arena, S., Tang, O., and Peron, M., Renewable hydrogen supply chains: A planning matrix and an agenda for future research, International Journal of Production Economics, 255, 108674, (2023).