Modeling of the strategic raw material supply for the European hydrogen target 2030: the case of x, y, and z

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Abstract

***Keywords*—**

1 Introduction

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3 Methodology

A deterministic bi-level optimization problem is proposed to answer the research questions. The lower-level problem considers market clearing under minimized total supply cost to satisfy the demand, and the upper-level problem is profit maximization of the major exporter with market power. The main link between the lower-level problem and the upper-level problem is the export price and quantity offered by the major exporter to the market clearing (i.e., decision variables from the upper-level problem serve as parameters for the lower-level problem) and the cleared quantity and price (i.e., decision variables from the follower and parameters for the upper-level problem). In the lower-level problem, the market clearing is treated separately for the European and global markets $M1$ and $M2$ (by having two separate supply-demand equilibrium constraints), but the total cost of both is minimized. As described in detail below, this allows for the consideration of customized conditions (such as diversification of exporters), especially in finding the optimality of the European market clearing. Against this background and also taking into account the market power of the major exporter, it is assumed that there is no price discrimination between the two markets under consideration in the long run. Therefore, the mathematical formulation of the lower-level problem ensures that the market clearing prices are uniform. There are many arguments that could be used to justify why the clearing market prices are converging here. To mention just a few: price arbitrage by traders between the different markets potentially equalizes market price differences when there are no significant barriers to entry or exit; provided that the different markets are transparent, consumers have the opportunity to compare market prices, which in turn, discourages exporters and sellers from offering different prices; and under the fact that the share of the transportation cost on the total cost does not dominate, as with the cost of critical raw materials.

3.1 Lower-level problem: market clearing at minimized total cost

As is typical for bi-level optimization problems, the original formulation (or primal problem) of the lower-level problem is transformed into its dual problem using the Karush-Kuhn-Tucker (KKT) solution formalism [1]. The complete formulation of the dual problem of the lower-level problem can be found in the Appendix A. For easiness of reading, the main text focuses on the original formulation and the primal problem of the lower-level problem.

3.1.1 Objective and decision variables

The objective of the lower-level problem is to minimize the total cost of supply when satisfying the demand of the European and global markets. Equation 1 shows the objective function while $\mathcal{X}$ is a vector and contains all the decision variables of the lower-level problem.

$$\min_{\mathcal{X}} \sum_{e} \sum_{m} \sum_{t} c_e \times q_{e,m,t} \tag{1}$$

The decision variables $q_{e,m,t}$ is the supply quantity of exporter e, market m, and timestep t. c_e is a parameter and describes the marginal supply cost per exporter e. The vector of decision variables is described in Equation 2

$$\mathcal{X} = [q_{e,m,t}, \underbrace{\bar{q}_{e,t}}_{\forall e \backslash \{i\},t}, q^{del}_{e,m,t}, q^{arb}_{e,m,t}] \tag{2}$$

where $\bar{q}_{e,t}$ is the available supply capacity per e and t, $q^{del}_{e,m,t}$ the cleared quantity delivered to m per e and t. $q^{arb}_{e,m,t}$ is a decision variable used solely to ensure uniform clearing prices between markets, as mentioned above. Essentially, this decision variable prevents exporters from engaging in price arbitrage.

Note, that $\bar{q}_{e,t}$ for the major export (index i) is a parameter for the lower-level problem, while it is a decision variable for the upper-level problem (see Section 3.2 in detail).

3.1.2 Constraints

The constraints of the primal problem are described below. For each constraint, the equation is given together with its applicability and the variable of the dual problem in parentheses. To help the reader understand the mathematical formulation of the model, the dual variables are numbered consecutively according to the equation number (see superscript of the dual variables). A distinction is also made between equality and inequality equations. Lambda (λ) is used for equality equations and mu (μ) for inequality equations. Table 1 outlines the mathematical formulation of the lower-level problem. The equations 3 and 4 ensure that the supply quantity is greater than or equal to zero and less than the available supply capacity per e and t.

$$0 \leq \sum_m q_{e,m,t} \quad : \forall e, t \quad (\mu^3_{e,t}) \tag{3}$$

$$\sum_m q_{e,m,t} \leq \bar{q}_{e,t} \quad : \forall e, t \quad (\mu^4_{e,t}) \tag{4}$$

The equation 5 separates the supply quantity into the cleared supply quantity delivered and is used to avoid arbitrage between markets and to unify prices (arbitrage). The equations 6 and 7 show the supply balances for each of the markets ($M1$ and $M2$). For example, the demand $d_{t,M1}$ is satisfied by the cleared supply quantity delivered and the quantity transferred from market $M2$. However, this rather general division between delivered and transferred quantities ultimately ensures that λ^6_t is equal to λ^7_t. Consequently, market clearing prices are uniform.

$$q_{e,m,t} = q^{del}_{e,m,t} + q^{arb}_{e,m,t} \quad : \forall e, m, t \quad (\lambda^5_{e,m,t}) \tag{5}$$

$$d_{M1,t} = \sum_e q^{del}_{e,M1,t} + q^{arb}_{e,M2,t} \quad : \forall t \quad (\lambda^6_t) \tag{6}$$

$$d_{M2,t} = \sum_e q^{del}_{e,M2,t} + q^{arb}_{e,M1,t} \quad : \forall t \quad (\lambda^7_t) \tag{7}$$

The equations 8 and 9 consider customized conditions for the clearing of the European market $M1$. The first equation takes into account the embargo of specific exporters and the second equation is the diversification of shares of exporters satisfying the demand. The latter limits the maximum share of an exporter to α of the total demand.

$$q_{e,M1,t} = 0 \quad : \forall e \in \mathcal{E}_{emb}, t \quad (\lambda^8_{e,t}) \tag{8}$$

$$q^{del}_{e,M1,t} + q^{arb}_{e,M2,t} \leq \alpha \times d_{M1,t} \quad : \forall e, t \quad (\mu^9_{e,t}) \tag{9}$$

The equations 10 to 13 ensure the non-negativity of the decision variables.

$$0 \leq q_{e,m,t} \quad : \forall e, m, t \quad (\mu^{10}_{e,m,t}) \tag{10}$$

$$0 \leq \bar{q}_{e,t} \quad : \forall e \setminus \{i\}, t \quad (\mu^{11}_{e,t}) \tag{11}$$

$$0 \leq q^{del}_{e,m,t} \quad : \forall e, m, t \quad (\mu^{12}_{e,m,t}) \tag{12}$$

$$0 \leq q^{arb}_{e,m,t} \quad : \forall e, m, t \quad (\mu^{13}_{e,m,t}) \tag{13}$$

The dual variables λ^6_t and λ^7_t (below just λ_t)are particularly important with regard to the following description of the upper-level problem. Both variables are directly incorporated in the objective function of the upper-level problem and thus in maximizing the profit of the major exporter. To take into account the impact of the market price not only on the decision and resulting outcome of the major exporter in the upper-level problem, the following approach is also chosen:

- The available supply capacity $\bar{q}_{e,t}$ of all exporters except the major exporter i (i.e., $\forall e \setminus \{i\}$) is assumed to be a function of the market clearing price λ_t.
- The equation 14 describes this relation. For reasons of simplification, it is assumed that more exporter's capacities are economically viable and can be made available to the market when market prices rise (for example as a result of the profit maximization strategy of the major exporter).
- However, there is no optimal capacity expansion. The available supply capacity is determined solely by the market clearing price of the previous one.

$$\bar{q}_{e,t} = f(\lambda_{t-1}) \quad \text{with } f = a + b \times \lambda_{t-1} \quad : \forall e \setminus \{i\}, t \setminus \{t_0 \tag{14}$$

The available supply capacity of the major exporter is not affected by the market clearing price, nor is it a decision variable in the lower-level problem. Before a detailed description of the upper-level problem is given, a few thoughts are added here to underscore the proposed approach, especially the relationship between the market-clearing price and the available supply capacity of exporters. Since there is little historical and empirical data on the evolution of markets for critical raw materials (including their prices), a look at other markets can be helpful. For example, the oil market. This market can serve as an example since similar market conditions can be assumed as in the markets for critical raw materials (e.g. high production concentration and thus market shares of a few exporters). A paper that explicitly examines the question of why oil prices jump is published by Wirl back in 2008 [2]. The author shows that the main reason for jumping oil prices is the strategic behavior (i.e. pricing) of exporters with market power. More specifically, he reveals that they seek hysteresis in the clearing price to maximize profits by crowding out other (smaller) exporters. Such jumping of prices is not only observed for the oil markets but also for other markets, such as the natural gas market (see for example Mason & Wilmot [3]).

3.2 Upper-level problem: profit maximization of the major exporter

As is often the case with bi-level optimization, the upper-level problem is much simpler than the lower-level problem. This leads in the case here to the fact, that the upper-level problem, which is the profit maximization of the major exporter (index i with refer to the lower-level problem from above) to the fact, that there are only two equations. The first, Equation 15, is the objective function of the problem. It shows the profit maximization of the major exporter by setting its decision variables.

$$\max_{\mathcal{Y}} \sum_{m} \sum_{t} q_{i,m,t} \times (\lambda_t - \tilde{c}) \tag{15}$$

The decision variables are summarized by $\mathcal{Y}$ and include the variables c_i and $\bar{q}_{i,t}$. This is also described in Equation 16. As a reminder, c_i is the marginal supply cost and $\bar{q}_{i,t}$ is the available supply capacity of the major exporter i at timestep t. Both variables are parameters in the lower-level problem.

$$\mathcal{Y} = [c_i, \bar{q}_{i,t}] \tag{16}$$

Essentially, the major exporter sets both variables so that the product of the cleared quantity delivered to the markets and the market clearing prices is maximized. Thereby, the only constraint is that the offered supply capacity is equal to or smaller than the real supply capacity which is assumed to be static over time. This is described in Equation 17.

$$0 \leq \bar{q}_{i,t} \leq \tilde{q}_i \tag{17}$$

3.3 Scenarios

3.4 Data

4 Results and discussion

5 Conclusion

Declaration of Competing Interest

The authors report no declarations of interest.

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