Modeling the supply of strategic raw materials for Europe's 2030 hydrogen target: analyzing dynamics, risks, and resilience

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Abstract

Keywords—

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Nomenclature

Type	Description	Unit
Set and index		
$e \in \mathcal{E} = \{1, \ldots, E\}$	Exporter, index by e (1…Major exporter)	
$e' \in \mathcal{E}' = \{2, \ldots, E\}$	Fringe exporter/supplier, index by e'	
$\underline{\boldsymbol{e}} \in \underline{\mathcal{E}} \subseteq \mathcal{E}$	Exporter subject to an embargo for the European market, index by $\underline{\boldsymbol{e}}$	
$m \in \mathcal{M} = \{M1, M2\}$	Market, index by m M1…European market, M2…Global market	
$t \in \mathcal{T} = \{2025, \ldots, 2040\}$	Time step, index by t	
$t' \in \mathcal{T}' \subseteq \mathcal{T}$	Time step without starting year 2025	
Decision variables of the lower-level problem		
$q_{e,m,t}$	Supply quantity per e, m, and t	ton
$\bar{q}_{e',t}$	Available supply capacity e' and t	ton/year
$\bar{q}^{add}_{e',t}$	Added available supply capacity per e' and t	ton/year
$\bar{q}^{retire}_{e',t}$	Retired supply capacity per e' and t	ton/year
$q^{arb}_{M1,M2,t}$	Arbitrage of supply quantity between the European market $M1$ and the global market $M2$	ton
$q^{del}_{1,m,t}$	Delivered supply quantity of the major exporter 1 per m and t	ton
$q^{arb}_{1,m,t}$	Arbitrage quantity of the major exporter 1 per m and t	ton
$q^{stock,in/out}_{M1,t}$	Quantity in or out of the stock for the European market $M1$	ton
$q^{stock,stored}_{M1,t}$	Stock stored for the European market $M1$ per t	ton
Decision variables of the upper-level problem		
$c_{1,t}$	Marginal supply cost of the major exporter 1 per t	€/ton
$\bar{q}_{1,t}$	Available supply capacity of the major exporter 1 per t	ton/year
Relevant parameters		
c^{gen}_{e}	Marginal supply cost per e and t	€/ton
$c^{main}_{e'}$	Specific maintenance cost per e'	€/ton/year
c^{stock}	Specific stockpiling cost	€/ton/year
$d_{m,t}$	Total demand per m and t	ton/year
α	Maximum supply share of the major exporter 1 at the European market $M1$	%

1 Introduction

2 Background

3 Methodology

A deterministic bi-level optimization problem is proposed to answer the research questions. The lower-level problem considers the behavior of competitive fringe supply, in which a fixed demand is met by minimizing supply cost by the fringe suppliers, given the upper-level decisions by the major exporter (Stackelberg leader). The leader maximizes its profit and can exercise market power. The main links between the lower-level problem and the upper-level problem are 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, in the other direction, the cleared quantity and price (i.e., decision variables from the lower-level, whose dependence on the upper-level variables is recognized by the leader). 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 (incl. Lagrangian function, KKT conditions, and complementarity conditions) can be found in Appendix A.1 and corresponding subsections. For easiness of reading, the main text focuses on the original formulation and the lower-level problem's primal problem.

3.1.1 Objective and decision variables

The objective of the lower-level problem is to minimize the sum of the generation cost of all exporters, the maintenance cost of fringe exporters, and the stockpiling cost of the European market when satisfying the demand of the European and global markets. Equation 1 shows the objective function while x is a vector containing all the lower-level problem's decision variables.

$$\min_{x} \underbrace{\sum_{e}\sum_{m}\sum_{t} c^{gen}_{e,t} \times q_{e,m,t}}_{\text{Generation cost of all exporters}} + \underbrace{\sum_{e'}\sum_{t} c^{main}_{e'} \times \bar{q}_{e',t}}_{\text{Maintenance cost of fringe exporters}} + \underbrace{\sum_{t} c^{stock} \times q^{stock,stored}_{M1,t}}_{\text{Stockpiling cost of European market}} \tag{1}$$

The decision variables $q_{e,m,t}$ is the supply quantity of exporter e, market m, and time step t. $c^{gen}_{e,t}$ is a parameter and describes the marginal supply cost per exporter e and time step t. Note that the latter varies over time for the major exporter only. For the fringe exporters, $c^{gen}_{e,t}$ is constant and assumed to be a single value over time. The decision variables $\bar{q}_{e',t}$ is the available supply capacity per fringe exporter e' and t. $c^{main}_{e',t}$ is a parameter and describes the specific maintenance cost per e'. In the third term, which considers the stockpiling cost of the European market $M1$, $q_{M1,t}^{stock,stored}$ is the decision variable of the stock stored for the European market per t. Again, c^{stock} is a parameter reflecting the specific stockpiling cost. The vector of decision variables is described in Equation 2.

$$x = [q_{e,m,t}, \bar{q}_{e',t}, \bar{q}_{e',t}^{add}, \bar{q}_{e',t}^{retire}, q_{M1,M2,t}^{arb}, q_{1,m,t}^{del}, q_{1,m,t}^{arb}, q_{M1,t}^{stock,in/out}, q_{M1,t}^{stock,stored}] \tag{2}$$

In addition to the decision variables described above, $\bar{q}_{e',t}^{add}$, $\bar{q}_{e',t}^{retire}$, $q_{M1,M2,t}^{arb}$, $q_{1,m,t}^{del}$, $q_{1,m,t}^{arb}$, and $q_{M1,t}^{stock,in/out}$ are introduced with x. $\bar{q}_{e',t}^{add}$ is the added available supply capacity per e' and t. $\bar{q}_{e',t}^{retire}$ is the retired supply capacity per e' and t. Both variables are directly influenced by the market clearing price of the previous time step $t-1$. This is explained in more detail in the Section 3.1.2 below. $q_{M1,M2,t}^{arb}$, $q_{1,m,t}^{del}$, and $q_{1,m,t}^{arb}$ are decision variables used solely to ensure uniform clearing prices between markets, as mentioned above. Essentially, this decision variable prevents exporters from engaging in price discrimination between the two markets. The quantity delivered to the market and used for arbitrage is explicitly considered for the major exporter ($q_{1,m,t}^{del}$, and $q_{1,m,t}^{arb}$), while an aggregate is considered for the sum of all the fringe exporters $q_{M1,M2,t}^{arb}$. A separate consideration for the major exporter is needed to ensure that major exporters' market share restrictions can be ensured when solving the model. $q_{M1,t}^{stock,in/out}$ is the quantity in or out of stock for the European market per t. Finally, note that $\bar{q}_{1,t}$ for the major export 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 lower level's 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 most relevant mathematical formulations of the lower-level problem.

Equation 3 ensures that the supply quantity is less than the available supply capacity per e and t (capacity restriction). Equation 4 is the balance constraint of the major exporter per m and t, ensuring that the supply quantity is either directly delivered to a market or through arbitrage to the other considered market.

$$\left[\sum_{m} q_{e,m,t}\right] - \bar{q}_{e,t} \leq 0 \quad : \forall e, t \quad (\mu_{e,t}^{3}) \tag{3}$$

$$q_{1,m,t}^{del} + q_{1,m,t}^{arb} - q_{1,m,t} = 0 \quad : \forall m, t \quad (\lambda_{m,t}^{4}) \tag{4}$$

The Equations 5 and 6 are the supply balance constraints of the European market $M1$ and the global market $M2$. Note that they differ in the way in which the European market allows stockpiling.

$$\left[\sum_{e'} q_{e',M1,t}\right] - q_{M1,M2,t}^{arb} + q_{1,M1,t}^{del} + q_{1,M2,t}^{arb} + q_{M1,t}^{stock,in/out} - d_{M1,t} = 0 \quad : \forall t \quad (\lambda_{t}^{5}) \tag{5}$$

$$\left[\sum_{e'} q_{e',M2,t}\right] + q_{M1,M2,t}^{arb} + q_{1,M2,t}^{del} + q_{1,M1,t}^{arb} - d_{M2,t} = 0 \quad : \forall t \quad (\lambda_{t}^{6}) \tag{6}$$

The demand of the European and global market per t is $d_{M1,t}$ and $d_{M2,t}$ respectively. Equation 7 considers the embargo on all exporters $\underline{\boldsymbol{e}}$ at the European market $M1$. Equation 8 considers the share restriction on the major exporter at the European market $M1$. The supply share of the major exporter is limited by the share of α of the total annual demand $d_{M1,t}$.

$$q_{e,M1,t} = 0 \quad : \forall \underline{\boldsymbol{e}}, \quad (\lambda^{7}_{\underline{\boldsymbol{e}},t}) \tag{7}$$

$$q^{del}_{1,M1,t} + q^{arb}_{1,M2,t} - \alpha \times d_{M1,t} \leq 0 \quad : \forall t \quad (\mu^{8}_{t}) \tag{8}$$

Equation 8 takes into account that the initial stock at the European market $M1$ is zero. Equation 10 is the stock balance constraint.

$$q^{stock,stored}_{M1,2025} = 0 \quad (\lambda^{9}) \tag{9}$$

$$q^{stock,stored}_{M1,t} - q^{stock,stored}_{M1,t-1} + q^{stock,in/out}_{M1,t} = 0 \quad : \forall t' \quad (\lambda^{10}_{t'}) \tag{10}$$

The equations 11 to 17 ensure the non-negativity of decision variables.

$$-q_{e,m,t} \leq 0 \quad : \forall e, m, t \quad (\mu^{11}_{e,m,t}) \tag{11}$$

$$-\bar{q}_{e',t} \leq 0 \quad : \forall e', t \quad (\mu^{12}_{e',t}) \tag{12}$$

$$-q^{del}_{1,m,t} \leq 0 \quad : \forall m, t \quad (\mu^{13}_{m,t}) \tag{13}$$

$$-q^{arb}_{1,m,t} \leq 0 \quad : \forall m, t \quad (\mu^{14}_{m,t}) \tag{14}$$

$$-q^{stock,stored}_{M1,t} \leq 0 \quad : \forall t \quad (\mu^{15}_{t}) \tag{15}$$

$$-\bar{q}^{add}_{e',t} \leq 0 \quad : \forall e', t \quad (\mu^{16}_{e',t}) \tag{16}$$

$$-\bar{q}^{retire}_{e',t} \leq 0 \quad : \forall t \quad (\mu^{17}_{e',t}) \tag{17}$$

The dual variables λ^5_t and λ^6_t (below just λ_t) are crucial 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. In order to consider the impact of the market price not only on the decision and the resulting outcome of the major exporter in the top-level problem, the following approach is also chosen: The available supply capacity $\bar{q}_{e',t}$ of all fringe exporters is assumed to be a function of the market clearing price λ_t. The equation 18 describes this relation. For 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, due to the profit maximization strategy of the major exporter).

$$\bar{q}_{e',t'} = \bar{q}_{e',t'-1} + \bar{q}^{add}_{e',t'} - \bar{q}^{retire}_{e',t'} \quad \text{with } \bar{q}^{add}_{e',t'} = f_e(\lambda_{t'-1}) \quad : \forall e', t' \tag{18}$$

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 useful. An example is 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 1 with refer to the lower-level problem from above) to the fact, that there are only two equations. The first, Equation 19, is the objective function of the problem. It shows the profit maximization of the major exporter by setting its decision variables.

$$\max_{\mathcal{Y}} \sum_m \sum_t q_{1,m,t} \times (\lambda_t - \tilde{c}) \tag{19}$$

The decision variables are summarized by $\mathcal{Y}$ and include the variables $c_{1,t}$ and $\bar{q}_{1,t}$. This is also described in Equation 20. As a reminder, $c_{1,t}$ is the marginal supply cost and $\bar{q}_{1,t}$ is the available supply capacity of the major exporter 1 at time step t. Both variables are parameters in the lower-level problem.

$$\mathcal{Y} = [c_{1,t}, \bar{q}_{1,t}] \tag{20}$$

Essentially, the major exporter sets both variables so that the product of the cleared quantity delivered to the markets and the market clearing prices are maximized. Thereby, the only constraint is that the offered supply capacity is equal to or smaller than the real supply capacity ($\tilde{q}_1$) which is assumed to be static over time. This is described in Equation 21.

$$0 \leq \bar{q}_{1,t} \leq \tilde{q}_1 \tag{21}$$

Further details on the mathematical formulation of the upper-level problem can be found A.2. Especially this section explains how the non-linear term $q_{1,m,t} \times \lambda_t$ is linearized.

Table 1: Summary of the mathematical formulation of the lower-level problem (market clearing at minimized total cost)

Equation			Qualitative/high-level explanation of the mathematical equation	
No.	Dim.	Dual var.	Keyword	Brief description
1	1	-	Objective	Minimize the sum of generation (all exporters), maintenance (fringe exporters), and stockpiling (European market $M1$) cost
3	$\lvert\mathcal{E}\rvert \times \lvert\mathcal{T}\rvert$	$\mu^3_{e,t}$	Capacity	Restrict supply quantity by available export capacity
4	$\lvert\mathcal{M}\rvert \times \lvert\mathcal{T}\rvert$	$\lambda^4_{m,t}$	Generation	Generation balance constraint of the major exporter 1
5	$\lvert\mathcal{T}\rvert$	λ^5_t	Market $M1$	Supply balance of the European market $M1$
6	$\lvert\mathcal{T}\rvert$	λ^6_t	Market $M2$	Supply balance of the global market $M2$
7	$\lvert\underline{\mathcal{E}}\rvert$	$\lambda^7_{\underline{e},t}$	Embargo	Embargo on exporters at the European market $M1$
8	$\lvert\mathcal{T}\rvert$	μ^8_t	Share	Restriction on the supply share of the major exporter 1 at the European market $M1$
9	1	λ_9	Initial stock	Set initial stock at the European market $M1$ zero
10	$\lvert\mathcal{T}'\rvert$	$\lambda^{10}_{t'}$	Stock balance	Stock balance constraint at the European market $M1$

3.3 Scenarios

MARZIA

3.4 Data

MAX

4 Results and discussion

5 Conclusion

Declaration of Competing Interest

The authors report no declarations of interest.

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References

[1] David Pozo, Enzo Sauma, and Javier Contreras. Basic theoretical foundations and insights on bilevel models and their applications to power systems. Annals of Operations Research, 254:303–334, 2017. doi: https://doi.org/10.1007/s10479-017-2453-z.

[2] Franz Wirl. Why do oil prices jump (or fall)? Energy Policy, 36(3):1029–1043, 2008. doi: https://doi.org/10.1016/j.enpol.2007.11.024.

[3] Charles F Mason and Neil A Wilmot. Jump processes in natural gas markets. Energy Economics, 46: S69–S79, 2014. doi: https://doi.org/10.1016/j.eneco.2014.09.015.

[4] Carlos Ruiz and Antonio J Conejo. Pool strategy of a producer with endogenous formation of locational marginal prices. IEEE Transactions on Power Systems, 24(4):1855–1866, 2009. doi: https://doi.org/10.1109/TPWRS.2009.2030378.

Appendices

A Mathematical formulation of the bi-level optimization problem

A.1 Lower-level problem: market clearing at minimized total cost

A.1.1 Primal decision variables

$$x = [q_{e,m,t}, \bar{q}_{e',t}, \bar{q}^{add}_{e',t}, \bar{q}^{retire}_{e',t}, q^{arb}_{M1,M2,t}, q^{del}_{1,m,t}, q^{arb}_{1,m,t}, q^{stock,in/out}_{M1,t}, q^{stock,stored}_{M1,t}] \tag{22}$$

A.1.2 Objective function

$$\min_{x} \underbrace{\sum_{e}\sum_{m}\sum_{t} c^{gen}_{e,t} \times q_{e,m,t}}_{\text{Generation cost of all exporters}} + \underbrace{\sum_{e'}\sum_{t} c^{main}_{e'} \times \bar{q}_{e',t}}_{\text{Maintenance cost of fringe exporters}} + \underbrace{\sum_{t} c^{stock} \times q^{stock,stored}_{M1,t}}_{\text{Stockpiling cost of European market}} \tag{23}$$

A.1.3 Constraints (primal problem)

Equality constraints

$$q^{del}_{1,m,t} + q^{arb}_{1,m,t} - q_{1,m,t} = 0 \quad : \forall m, t \quad (\lambda^{4}_{m,t}) \tag{24}$$

$$\left[\sum_{e'} q_{e',M1,t}\right] - q^{arb}_{M1,M2,t} + q^{del}_{1,M1,t} + q^{arb}_{1,M2,t} + q^{stock,in/out}_{M1,t} - d_{M1,t} = 0 \quad : \forall t \quad (\lambda^{5}_{t}) \tag{25}$$

$$\left[\sum_{e'} q_{e',M2,t}\right] + q^{arb}_{M1,M2,t} + q^{del}_{1,M2,t} + q^{arb}_{1,M1,t} - d_{M2,t} = 0 \quad : \forall t \quad (\lambda^{6}_{t}) \tag{26}$$

$$q_{e,M1,t} = 0 \quad : \forall \underline{\boldsymbol{e}}, \quad (\lambda^{7}_{\underline{\boldsymbol{e}},t}) \tag{27}$$

$$q^{stock,stored}_{M1,2025} = 0 \quad (\lambda^{9}) \tag{28}$$

$$q^{stock,stored}_{M1,t} - q^{stock,stored}_{M1,t-1} + q^{stock,in/out}_{M1,t} = 0 \quad : \forall t' \quad (\lambda^{10}_{t'}) \tag{29}$$

Inequality constraints

$$\left[\sum_{m} q_{e,m,t}\right] - \bar{q}_{e,t} \leq 0 \quad : \forall e, t \quad (\mu^{3}_{e,t}) \tag{30}$$

$$q^{del}_{1,M1,t} + q^{arb}_{1,M2,t} - \alpha \times d_{M1,t} \leq 0 \quad : \forall t \quad (\mu^{8}_{t}) \tag{31}$$

$$-q_{e,m,t} \leq 0 \quad : \forall e, m, t \quad (\mu^{11}_{e,m,t}) \tag{32}$$

$$-\bar{q}_{e',t} \leq 0 \quad : \forall e', t \quad (\mu^{12}_{e',t}) \tag{33}$$

$$-q^{del}_{1,m,t} \leq 0 \quad : \forall m, t \quad (\mu^{13}_{m,t}) \tag{34}$$

$$-q^{arb}_{1,m,t} \leq 0 \quad : \forall m, t \quad (\mu^{14}_{m,t}) \tag{35}$$

$$-q^{stock,stored}_{M1,t} \leq 0 \quad : \forall t \quad (\mu^{15}_{t}) \tag{36}$$

A.1.4 Dual decision variables

$$\lambda = [\lambda^4_{m,t}, \lambda^5_t, \lambda^6_t, \lambda^7_{\underline{e},t}, \lambda^9, \lambda^{10}_{t'}] \tag{37}$$

$$\mu = [\mu^3_{e,t}, \mu^8_t, \mu^{11}_{e,m,t}, \mu^{12}_{e',t}, \mu^{13}_{m,t}, \mu^{14}_{m,t}, \mu^{15}_t] \tag{38}$$

A.1.5 Lagrangian function

$$
\begin{aligned}
\mathcal{L}(x,\lambda,\mu) = &\sum_{e}\sum_{m}\sum_{t} c^{gen}_{e,t} \times q_{e,m,t} + \sum_{e'}\sum_{t} c^{main}_{e'} \times \bar{q}_{e',t} + \sum_{t} c^{stock} \times q^{stock,stored}_{M1,t} \\
&+ \sum_{m}\sum_{t} \lambda^{4}_{m,t} \times \left\{ q^{del}_{1,m,t} + q^{arb}_{1,m,t} - q_{1,m,t} \right\} \\
&+ \sum_{t} \lambda^{5}_{t} \times \left\{ \left[\sum_{e'} q_{e',M1,t} \right] - q^{arb}_{M1,M2,t} + q^{del}_{1,M1,t} + q^{arb}_{1,M2,t} + q^{stock,in/out}_{M1,t} - d_{M1,t} \right\} \\
&+ \sum_{t} \lambda^{6}_{t} \times \left\{ \left[\sum_{e'} q_{e',M2,t} \right] + q^{arb}_{M1,M2,t} + q^{del}_{1,M2,t} + q^{arb}_{1,M1,t} - d_{M2,t} \right\} \\
&+ \sum_{\underline{e}}\sum_{t} \lambda^{7}_{\underline{e},t} \times \left\{ q_{\underline{e},M1,t} \right\} \\
&+ \lambda^{9} \times \left\{ q^{stock,stored}_{M1,2025} \right\} \\
&+ \sum_{t'} \lambda^{10}_{t'} \times \left\{ q^{stock,stored}_{M1,t'} - q^{stock,stored}_{M1,t'-1} + q^{stock,in/out}_{M1,t'} \right\} \\
&+ \sum_{e}\sum_{t} \mu^{3}_{e,t} \times \left\{ \left[\sum_{m} q_{e,m,t} \right] - \bar{q}_{e,t} \right\} \\
&+ \sum_{t} \mu^{8}_{t} \times \left\{ q^{del}_{1,M1,t} + q^{arb}_{1,M2,t} - \alpha \times d_{M1,t} \right\} \\
&+ \sum_{e}\sum_{m}\sum_{t} \mu^{11}_{e,m,t} \times \left\{ -q_{e,m,t} \right\} \\
&+ \sum_{e'}\sum_{t} \mu^{12}_{e',t} \times \left\{ -\bar{q}_{e',t} \right\} \\
&+ \sum_{m}\sum_{t} \mu^{13}_{m,t} \times \left\{ -q^{del}_{1,m,t} \right\} \\
&+ \sum_{m}\sum_{t} \mu^{14}_{m,t} \times \left\{ -q^{arb}_{1,m,t} \right\} \\
&+ \sum_{t} \mu^{15}_{t} \times \left\{ -q^{stock,stored}_{M1,t} \right\}
\end{aligned} \tag{39}
$$

A.1.6 Karush–Kuhn–Tucker conditions

$$
\frac{\partial \mathcal{L}}{\partial q_{e,m,t}} = \begin{cases}
c^{gen}_{1,t} - \lambda^{4}_{m,t} + \mu^{3}_{1,t} - \mu^{11}_{1,m,t} = 0 & : \forall m,t \text{ if } 1 \notin \underline{\mathcal{E}} \\
c^{gen}_{1,t} - \lambda^{4}_{m,t} + \lambda^{7}_{1,t} + \mu^{3}_{1,t} - \mu^{11}_{1,m,t} = 0 & : \forall m,t \text{ if } 1 \in \underline{\mathcal{E}} \\
c^{gen}_{e',t} + \lambda^{5}_{t} + \mu^{3}_{e',t} - \mu^{11}_{e',M1,t} = 0 & : \forall e' \notin \underline{\mathcal{E}}, t \\
c^{gen}_{e',t} + \lambda^{5}_{t} + \lambda^{7}_{e',t} + \mu^{3}_{e',t} - \mu^{11}_{e',M1,t} = 0 & : \forall e' \in \underline{\mathcal{E}}, t \\
c^{gen}_{e',t} + \lambda^{6}_{t} + \mu^{3}_{e',t} - \mu^{11}_{e',M2,t} = 0 & : \forall e' \notin \underline{\mathcal{E}}, t \\
c^{gen}_{e',t} + \lambda^{6}_{t} + \lambda^{7}_{e',t} + \mu^{3}_{e',t} - \mu^{11}_{e',M2,t} = 0 & : \forall e' \in \underline{\mathcal{E}}, t
\end{cases} \tag{40}
$$

$$
\frac{\partial \mathcal{L}}{\partial \bar{q}_{e',t}} = c^{main}_{e',t} + \mu^{3}_{e',t} - \mu^{12}_{e',t} = 0 \quad : \forall e', t \tag{41}
$$

$$\frac{\partial \mathcal{L}}{\partial q^{arb}_{M1,M2,t}} = -\lambda^5_t + \lambda^6_t = 0 \quad : \forall t \tag{42}$$

$$\frac{\partial \mathcal{L}}{\partial q^{del}_{1,m,t}} = \begin{cases} \lambda^4_{M1,t} + \lambda^5_t + \mu^8_t - \mu^{13}_{M1,t} = 0 & : \forall t \\ \lambda^4_{M2,t} + \lambda^6_t - \mu^{13}_{M2,t} = 0 & : \forall t \end{cases} \tag{43}$$

$$\frac{\partial \mathcal{L}}{\partial q^{arb}_{1,m,t}} = \begin{cases} \lambda^4_{M1,t} + \lambda^6_t - \mu^{14}_{M1,t} = 0 & : \forall t \\ \lambda^4_{M2,t} + \lambda^5_t + \mu^8_t - \mu^{14}_{M2,t} = 0 & : \forall t \end{cases} \tag{44}$$

$$\frac{\partial \mathcal{L}}{\partial q^{stock,in/out}_{M1,t}} = \begin{cases} \lambda^5_{2025} - \mu^{15}_{2025} = 0 \\ \lambda^5_{t'} + \lambda^{10}_{t'} - \mu^{15}_{t'} = 0 & : \forall t' \end{cases} \tag{45}$$

$$\frac{\partial \mathcal{L}}{\partial q^{stock,stored}_{M1,t}} = \begin{cases} c^{stock} + \lambda^9 - \lambda^{10}_{2025} + \lambda^{10}_{2026} = 0 \\ c^{stock} - \lambda^{10}_{t'} + \lambda^{10}_{t'+1} & : \forall t' \setminus \{2040\} \end{cases} \tag{46}$$

$$0 \leq \mu^3_{e,t} \quad \perp \quad \left[\sum_m q_{e,m,t}\right] - \bar{q}_{e,t} \leq 0 \quad : \forall e, t \tag{47}$$

$$0 \leq \mu^8_t \quad \perp \quad q^{del}_{1,M1,t} + q^{arb}_{1,M2,t} - \alpha \times d_{M1,t} \leq 0 \quad : \forall t \tag{48}$$

$$0 \leq \mu^{11}_{e,m,t} \quad \perp \quad -q_{e,m,t} \leq 0 \quad : \forall e, m, t \tag{49}$$

$$0 \leq \mu^{12}_{e',t} \quad \perp \quad -\bar{q}_{e',t} \leq 0 \quad : \forall e', t \tag{50}$$

$$0 \leq \mu^{13}_{m,t} \quad \perp \quad -q^{del}_{1,m,t} \leq 0 \quad : \forall m, t \tag{51}$$

$$0 \leq \mu^{14}_{m,t} \quad \perp \quad -q^{arb}_{1,m,t} \leq 0 \quad : \forall m, t \tag{52}$$

$$0 \leq \mu^{15}_t \quad \perp \quad -q^{stock,stored}_{M1,t} \leq 0 \quad : \forall m, t \tag{53}$$

A.1.7 Complementarity condition linearization

The complementarity conditions in Equations 47 to 53 are linearized using the well-known linear expressions (see [4]) as follows, where u is a binary decision variable and M is a parameter large enough to ensure complementarity (both indexed accordingly).

$$\begin{aligned} 0 \leq \mu^3_{e,t} \leq M^3 \times u^3_{e,t} \quad &: \forall e, t \\ 0 \leq \left[\sum_m q_{e,m,t}\right] - \bar{q}_{e,t} \leq M^3 \times \left(1 - u^3_{e,t}\right) \quad &: \forall e, t \end{aligned} \tag{54}$$

$$\begin{aligned} 0 \leq \mu^8_t \leq M^8 \times u^8_{e,t} \quad &: \forall t \\ 0 \leq q^{del}_{1,M1,t} + q^{arb}_{1,M2,t} - \alpha \times d_{M1,t} \leq M^8 \times \left(1 - u^8_t\right) \quad &: \forall t \end{aligned} \tag{55}$$

$$\begin{aligned} 0 \leq \mu^{11}_{e,m,t} \leq M^{11} \times u^{11}_{e,m,t} \quad &: \forall e, m, t \\ 0 \leq q_{e,m,t} \leq M^{11} \times \left(1 - u^{11}_{e,m,t}\right) \quad &: \forall e, m, t \end{aligned} \tag{56}$$

$$\begin{aligned} 0 \leq \mu^{12}_{e',t} \leq M^{12} \times u^{12}_{e',t} \quad &: \forall e', t \\ 0 \leq \bar{q}_{e',t} \leq M^{12} \times \left(1 - u^{12}_{e',t}\right) \quad &: \forall e', t \end{aligned} \tag{57}$$

$$\begin{aligned} 0 \leq \mu^{13}_{m,t} \leq M^{13} \times u^{13}_{m,t} \quad &: \forall m, t \\ 0 \leq q^{del}_{1,m,t} \leq M^{13} \times \left(1 - u^{13}_{m,t}\right) \quad &: \forall m, t \end{aligned} \tag{58}$$

$$\begin{aligned} 0 \leq \mu^{14}_{m,t} \leq M^{14} \times u^{14}_{m,t} \quad &: \forall m, t \\ 0 \leq q^{arb}_{1,m,t} \leq M^{14} \times \left(1 - u^{14}_{m,t}\right) \quad &: \forall m, t \end{aligned} \tag{59}$$

$$\begin{aligned} 0 \leq \mu^{15}_t \leq M^{15} \times u^{15}_t \quad &: \forall t \\ 0 \leq q^{stock,stored}_{M1,t} \leq M^{15} \times \left(1 - u^{15}_t\right) \quad &: \forall t \end{aligned} \tag{60}$$

A.2 Upper-level problem: profit maximization of the major exporter

A.2.1 Decision variables

$$\mathcal{Y} = [c_{1,t}, \bar{q}_{1,t}] \tag{61}$$

A.2.2 Objective function

$$\max_{\mathcal{Y}} \sum_m \sum_t q_{1,m,t} \times (\lambda_t - \tilde{c}) \tag{62}$$

A.2.3 Constraints

$$0 \leq \bar{q}_{1,t} \leq \tilde{q}_1 \tag{63}$$

A.2.4 Linear reformulation

- Of the non-linear term $q_{1,m,t} \times \lambda_t$ (see Equation 62)
- With m,n in [($M1$, 5), ($M2$, 6)] (see Equations 25 and 26)
- With the following new variables: $\sigma_{e,m,t}$ (binary), $\tilde{\lambda}^n_{e,t}$ (continuous), $\tilde{\sigma}_{e,m,t}$ (binary)
- With the following new parameters: $\tilde{\beta}$ (large enough), ϵ (small enough)

$$\lambda_t = \lambda^n_t = \sum_{e'} c_{e'} \times \sigma_{e',m,t} \quad : \forall t, m, n \tag{64}$$

$$\sum_{e'} \sigma_{e',m,t} = 1 \quad : \forall t, m \tag{65}$$

$$\tilde{\lambda}^n_{e',t} = c_{e'} \times \tilde{\sigma}_{e',m,t} \quad : \forall e', m, t \tag{66}$$

$$q_{e',m,t} \leq \tilde{\beta} \times \tilde{\sigma}_{e',m,t} \quad : \forall e', m, t \tag{67}$$

$$q_{e',m,t} \geq \epsilon \times \tilde{\sigma}_{e',m,t} \quad : \forall e', m, t \tag{68}$$

$$\sigma_{e',m,t} \leq \tilde{\sigma}_{e',m,t} \quad : \forall e', m, t \tag{69}$$

$$\lambda^n_t \geq \tilde{\lambda}^n_{e',t} \quad : \forall e', t, n \tag{70}$$

- Introducing the following new variable $z_{e',m,t}$ (continuous) and parameter β (large enough)

$$z_{e',m,t} \leq \beta \times \sigma_{e',m,t} \quad : \forall e', m, t \tag{71}$$

$$z_{e',m,t} \leq q_{1,m,t} \quad : \forall e', m, t \tag{72}$$

$$z_{e',m,t} \geq q_{1,m,t} - \left(1 - \sigma_{e',m,t}\right) \times \beta \quad : \forall e', m, t \tag{73}$$

$$z_{e',m,t} \geq 0 \quad : \forall e', m, t \tag{74}$$

A.3 Completed optimization problem

$$\max_{x,\lambda,\mu,u,y,\sigma,z} \sum_m \sum_t \sum_{e'} c_{e'} \times z_{e',m,t} - \sum_m \sum_t q_{1,m,t} \times \tilde{c}$$

$$\begin{aligned} \text{s.t. } (40) &- (46) \\ (54) &- (60) \\ (63) &- (74) \\ &(18) \end{aligned} \tag{75}$$

B Data

MAX