“If you are receptive and humble**, mathematics will lead you by the hand.”**

As quoted in The Strangest Man: The Hidden Life of Paul Dirac, Mystic of the Atom (2009) by Graham Farmelo, p. 435

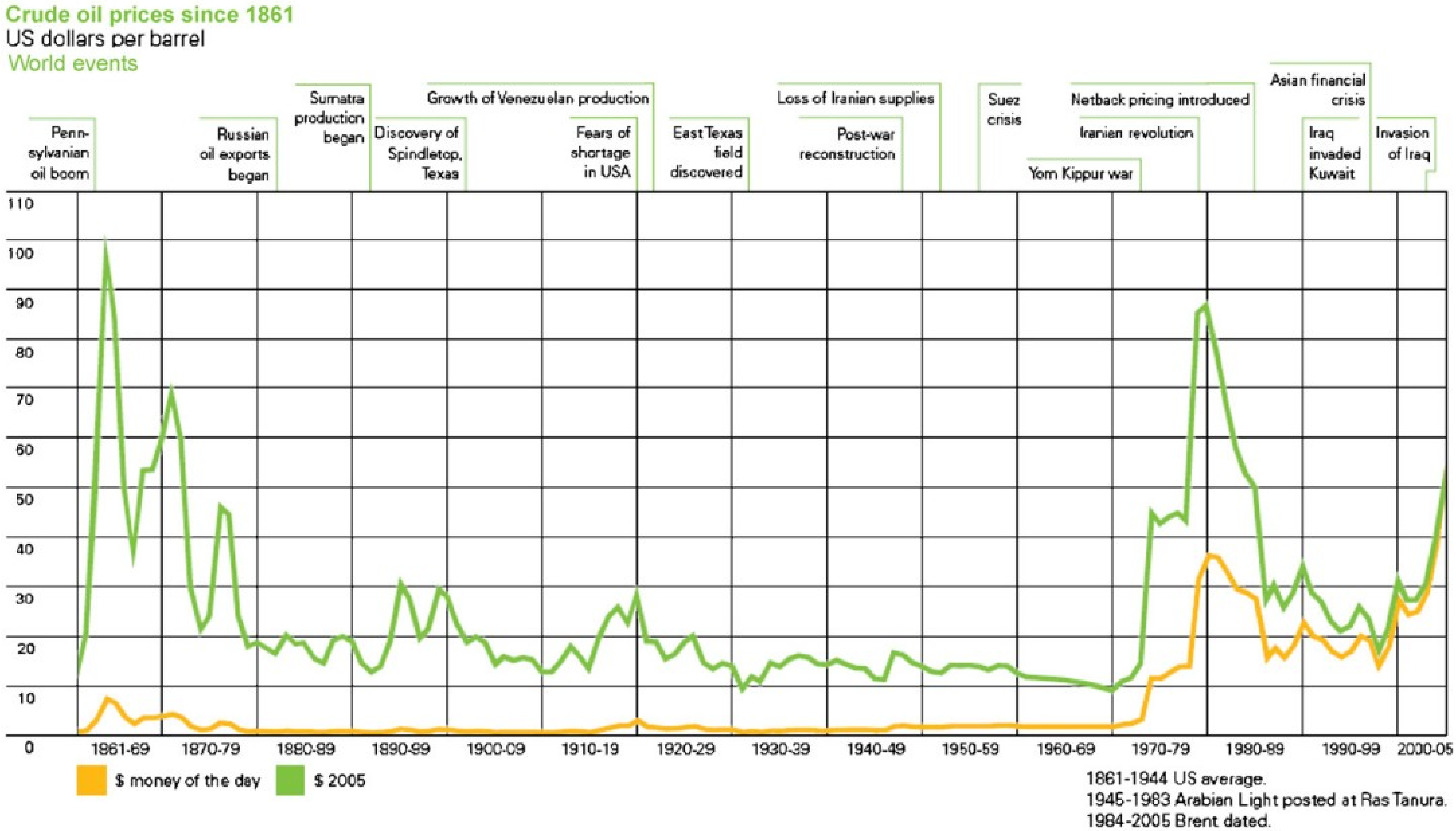

Fig. 1. Oil price evolution, 1861–2005, BP Statistical Review of World Energy 2006.

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Why do oil prices jump (or fall)?

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Gold
Silver
Platinum
Palladium
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6h
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1m
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Modeling the supply of strategic raw materials for Europe’s 2030 hydrogen target: analyzing dynamics, risks, and resilience

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Crude oil vs. critical raw material supply: a few notes

Global platinum reserves

Region	Variable	Unit	Year	Value
World	Reserves|Platinum	ton	2022	70 000
South Africa	Reserves|Platinum	ton	2022	63 000
Russia	Reserves|Platinum	ton	2022	5 500
Zimbabwe	Reserves|Platinum	ton	2022	1 200
United States	Reserves|Platinum	ton	2022	900
Canada	Reserves|Platinum	ton	2022	310

Global annual demand in the range of 220 tons per year.

Platinum production cost

Region	Variable	Unit	Year	Value
South Africa	Average Production Cost|Platinum	EUR/ton	2018	€ 26 823 207.13
North Americ	Average Production Cost|Platinum	EUR/ton	2018	€ 21 785 345.90
Zimbabwe	Average Production Cost|Platinum	EUR/ton	2018	€ 21 431 334.03
Russia	Average Production Cost|Platinum	EUR/ton	2018	€ 13 942 621.37
World	Average Production Cost|Platinum	EUR/ton	2018	€ 20 151 444.95

Thomson Reuters, & GFMS. (May 31, 2019). Production costs of platinum by selected region from 2013 to 2018.

Platinum supply and demand

'000 oz	PGM market report series 2009	2010	2011	2012	2013	PGM market report series 2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Primary supply															
South Africa	4 635	4 635	4 860	4 110	4 208	3 546	4 572	4 392	4 450	4 467	4 344	3 243	4 609	3 965	4 154
Russia	785	825	835	801	736	700	670	714	720	687	721	699	638	600	630
North America	260	200	350	306	322	346	354	370	368	370	367	334	279	266	288
Zimbabwe	230	280	340	337	410	401	400	489	466	474	451	482	465	488	529
Others	115	110	100	126	174	167	158	162	157	152	154	205	222	211	207
Total primary supply	**6 025**	**6 050**	**6 485**	**5 680**	**5 850**	**5 160**	**6 154**	**6 127**	**6 161**	**6 150**	**6 037**	**4 963**	**6 213**	**5 530**	**5 808**
Secondary supply															
Automotive	830	1 085	1 240	1 120	1 186	1 235	1 147	1 132	1 249	1 332	1 389	1 154	1 234	1 153	1 200
Electronics/other	10	10	10	22	24	28	30	32	35	38	40	38	44	51	56
Jewellery	565	735	810	895	790	762	574	738	746	699	663	506	367	264	265
Total secondary supply	**1 405**	**1 830**	**2 060**	**2 037**	**2 000**	**2 025**	**1 751**	**1 902**	**2 030**	**2 069**	**2 092**	**1 698**	**1 645**	**1 468**	**1 521**
Total combined supply	**7 430**	**7 880**	**8 545**	**7 717**	**7 850**	**7 185**	**7 905**	**8 029**	**8 191**	**8 219**	**8 129**	**6 661**	**7 858**	**6 998**	**7 329**
Demand by application															
Auto (6)	2 185	3 075	3 185	3 158	2 827	2 888	3 134	3 165	3 061	2 815	2 589	2 024	2 405	2 762	3 063
Chemical	290	440	470	452	522	576	502	477	453	654	665	615	677	699	697
Dental & Biomedical (3)	250	230	230	223	217	214	227	227	238	241	254	218	224	253	257
Electrical & Electronics (1)	190	230	230	176	219	224	227	227	224	228	215	226	259	235	266
Glass	10	385	515	153	102	143	227	247	314	501	468	507	908	594	565
Investment (2)	660	655	460	450	871	277	451	620	361	67	1 131	1 022	-28	-565	283
Jewellery* (1)	2 810	2 420	2 475	2 783	2 984	2 839	2 746	2 413	2 385	2 258	2 073	1 657	1 468	1 344	1 351
Petroleum	210	170	210	112	146	172	140	186	228	380	262	287	216	230	213
Pollution Control (5)					143	168	172	189	184	193	190	175	205	223	260
Other	190	300	320	395	388	438	464	498	530	531	542	417	444	483	502
Demand	**6 795**	**7 905**	**8 095**	**7 902**	**8 419**	**7 939**	**8 290**	**8 249**	**7 978**	**7 868**	**8 389**	**7 148**	**6 778**	**6 258**	**7 457**
Western sales to China & E. Europe (4)															
Total Demand	**6 795**	**7 905**	**8 095**	**7 902**	**8 419**	**7 939**	**8 290**	**8 249**	**7 978**	**7 868**	**8 389**	**7 148**	**6 778**	**6 258**	**7 457**
Movements in stocks	**635**	-25	**450**	-185	-569	-754	-385	-220	**213**	**351**	-260	-487	**1 080**	**740**	-128

The EU's critical raw material act (released in March 2023)

The EU is aiming to ensure a secure and sustainable supply of critical raw materials for Europe's industry.

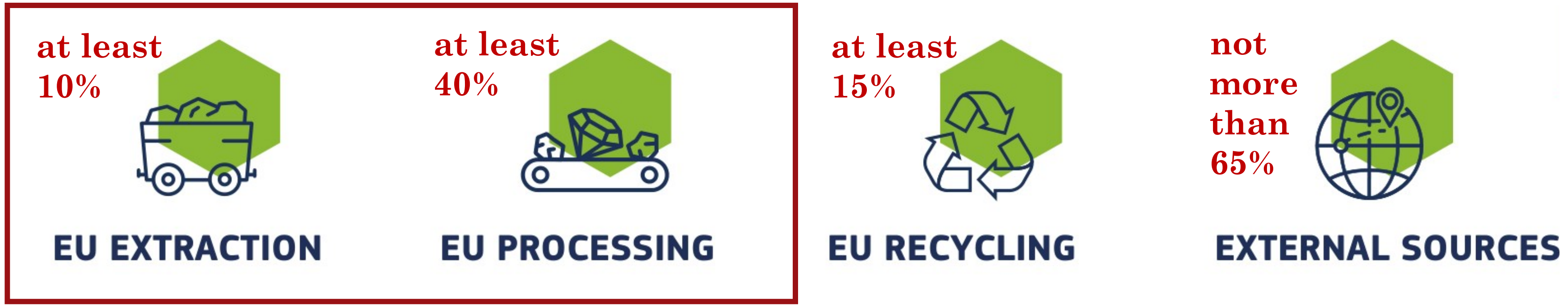
- Critical raw materials (CRMs) are needed for the green and digital transitions
  - are at the beginning of many industrial supply chains
  - their global demand is increasing (key components of wind turbines, batteries, etc.)
- To enhance long-term competitiveness
- To maintain our open strategic autonomy in a fast-changing and increasingly challenging geopolitical environment
- EU demand for lithium batteries powering electric vehicles set to increase 12 times by 2030
- EU demand for rare earth metals set to rise 5 to 6 by 2030

CRM: 1 of 2

Source: European Critical Raw Material Act

The EU’s critical raw material act

Europe faces dependencies on key critical raw materials.



- 63% of the world’s cobalt is extracted om the Democratic Republic of Congo, while 60% is refined in China.
- 97% of EU’s magnesium supply is sourced from China.
- 100% of the rare earths used for permanent magnets globally are refined in China.
- South Africa provides 71% of the EU’s needs for platinum group metals.

Source: European Critical Raw Material Act

EU’s hydrogen target by 2030 and our core objective

2022’s “REPower EU” plan highlights investments in renewable energy, with a 10 bcm H2 production target by 2030.

- Leading to a projected sharp increase in electrolyze and fuel cell capacity
  - increase in demand for platinum by 24%, iridium 43%, and scandium 68% by 2030 (IEA, 2022)

- Focusing on the need for critical raw materials in the hydrogen economy uptake, our paper examines:
  - The interaction between the dominant player in the market for platinum and the EU.
  - In light of global demand for CRMs, the work assesses whether the CRM Act contributes to the resilience of Europe’s CRM supply chain, particularly in addressing the potential risks associated with its ambitious hydrogen domestic production targets by 2030.
  - It investigates the impact of the market-dominant player's strategic behavior, encompassing factors such as supply disruptions, on the European supply chain for platinum, crucial for hydrogen production.

Research questions

1. How does the **main player's strategic** dominance in the platinum market influence the EU's supply chain dynamics, particularly in terms of supply chain dependency, vulnerability to disruptions, and the impact on technological innovation, and what are the long-term implications for the European CRM sector?

2. To what extent does the **CRM Act**, through provisions compliance and effectiveness in promoting diversification, contribute to reducing the EU's dependency on the dominant player REEs, creating a more resilient CRM supply chain, and fostering technological innovation in the platinum sector?

3. How do the **stockpiling** provisions of the CRM Act mitigate the impact of geopolitical tensions and supply disruptions on the EU's REEs supply chain, and to what extent do these provisions contribute to the resilience of the supply chain, address challenges in meeting hydrogen production targets, and influence strategic decision-making amid **market uncertainties and volatility**?

Literature review

As far as the proposed techno-economic modeling approach is concerned, to the best of our knowledge there is no equivalent publication. Still, the literature offers studies that are worth mentioning.

- A focus of existing studies is certainly the modeling of the CRM **demand** and requirements in techno-economic, mostly large-scale energy system models
(e.g., Liang (2022), Zhang (2023), Tokimatsu (2017), and Peiró (2022)).

- Another strand of the existing literature deals with the **prices** of CRMs and how they might evolve in the context of an expected significant increase during the sustainable transition of the global energy system.
(e.g., Sun (2011), Schnuelle (2019), Parra and Patel (2016), Robinson (2017), Bao (2020))

- Another interesting aspect is the **secondary supply and the recycling** of CRMs.
  - The current literature already provides plenty of studies dealing, for example, with the recycling of steel and iron from a techno-economic perspective but hardly any about CRMs especially platinum. (one exception: Tong (2022))

Proposed bi-level optimization model (overview)

- 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 her 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[1] and, in the other direction, the cleared quantity and price[2].
- 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.

[1]Decision variables from the upper-level problem serve as parameters for the lower-level problem.
[2]Decision variables from the lower-level, whose dependence on the upper-level variables is recognized by the leader

The basics of bi-level optimization (1 / 2)

An upper-level feasible solution must be an optimal lower-level solution.

1. Sequential game: the upper-level (leader) acts first, then the lower-level (follower).
2. Therefore, full information about the lower-level problem (objective, constraints, etc.) of the upper-level problem is assumed.
3. In other words, equilibrium means that neither the leader nor the follower can improve its objective (function value) by a change in strategy.

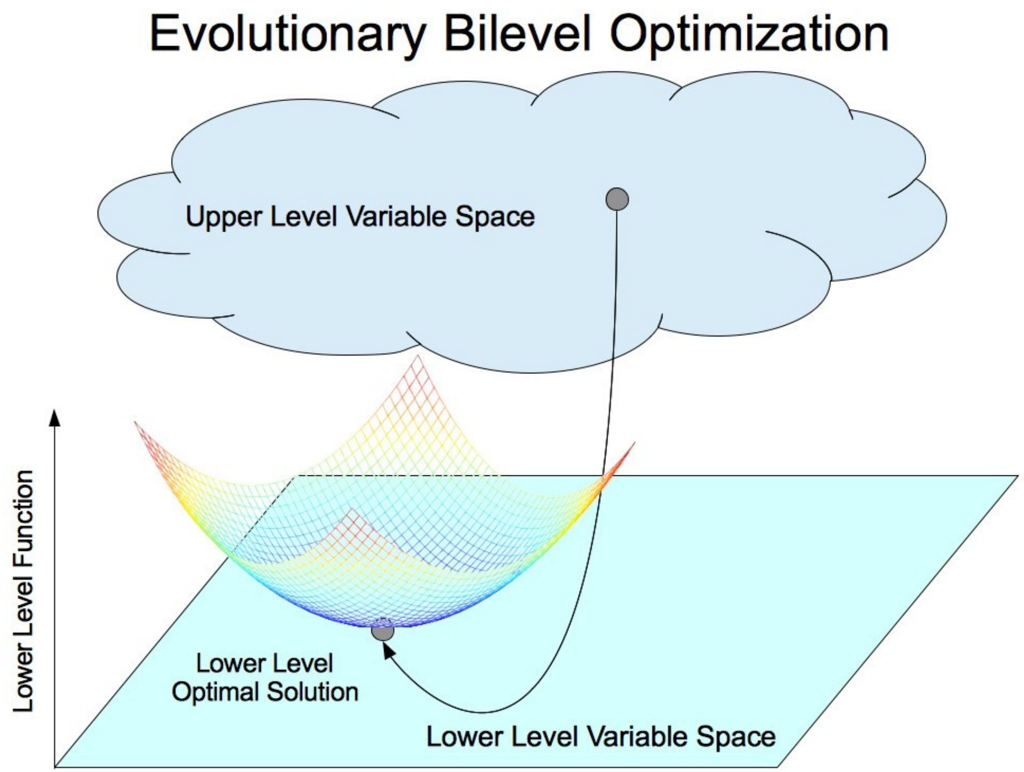


Figure: Evolutionary bilevel optimization

Lower-level problem (market clearing at minimized total cost)

The objective 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.

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

- Retrieved quantity per exporter (e), market (m), and time (t)
- Available yearly generation capacity per fringe exporter (e'), and time (t)
- Stocked stored at the European Market (M1) per time (t)
- Specific generation cost per exporter (e'), and time (t)
- Specific maintenance cost of available generation capacity per fringe exporter (e')

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. There are only two equations: the objective function (top) and a capacity constraint.

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

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

Key takeaways

- Not much literature exists dealing with the techno-economic modeling of critical raw material supply for the decarbonization of energy systems (this is especially true for platinum)
- Advanced modeling techniques are likely to be required for the modeling, as traditional cost-minimizing approaches do not adequately represent the expected market situation.

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