engineering proceedings

MDPI

Proceeding Paper

The Clean Energy Transition and the Rare Earth Industry †

Al Thibeault

Energy & Petroleum Engineering, College of Engineering & Mines, University of North Dakota, Grand Forks, ND 58202, USA; al.thibeault@und.edu

† Presented at the 1st International Conference on Industrial, Manufacturing, and Process Engineering (ICIMP-2024), Regina, Canada, 27–29 June 2024.

Abstract: The clean energy transition is dependent on several of the critical minerals, including rare earths. The global rare earth industry (REI), which supplies these rare earths, is itself in a period of transition. A successful REI transition requires a secure and stable supply of rare earths to meet the demands of the global clean energy transition. Achieving these success criteria requires (1) re-establishing diversified rare earth production and (2) finding new sources of competitive advantage to create long-term stability for the diversified industry. Results from a simulation model testing various transition strategies based on an interdisciplinary transition approach are promising.

Keywords: rare earth; competitive advantage; hybrid dynamic simulation; clean energy

check for updates

Citation: Thibeault, A. The Clean Energy Transition and the Rare Earth Industry. *Eng. Proc.* **2024**, *76*, 62. https://doi.org/10.3390/engproc2024076062

Academic Editors: Golam Kabir, Sharfuddin Khan, Mohammad Khondoker and Hussameldin Ibrahim

Published: 30 October 2024

1. Introduction

The global rare earth industry (REI) is comprised of firms in over 20 nations engaged in one or more of the three stages of production—upstream (extraction and concentration), midstream (separation), and downstream (refining and fabrication). The size of the REI market is approximately USD 10 billion. While there are 17 rare earth elements, 94% of the market value is for the four rare earth elements used in the manufacture of permanent magnets: neodymium (Nd, 59%), praseodymium (Pr, 15%), dysprosium (Dy, 11%), and terbium (Tb, 9%) [1]. The importance of these four rare earths is summarized by the International Energy Agency (IEA) thusly: "Rare earth elements (REEs) are essential for permanent magnets required by EVs and wind turbines [2]".

Given the importance of REEs, and hence the REI, to the clean energy transition, the secure and stable supply of REEs becomes of prime importance. Concern that their supply is not secure and stable is underlined by REEs being the only material included on the critical mineral lists of all seventeen Minerals Security Partnership (MSP) countries [3].

The MSP countries are a block of countries formed with a mandate to improve the security and stable supply of REEs, which is currently dominated, in all three stages of production, by China. At the end of 2022, China, primarily through State-owned Enterprises (SOEs), was responsible for 70%, 85%, and 92% of global upstream, midstream, and downstream production, respectively. REE supply and security risks were amply demonstrated in 2010 when a brief export embargo by China of REEs to Japan triggered a market reaction that saw prices surge by as much as 4000% before returning to normal levels by 2014.

Figure 1 shows a highly aggregated view of factors involved in coupling the clean energy transition and the REI transition. The drawing incorporates concepts from systems engineering [4] and socio-technical energy transitions (STET) [5]. The primary coupling factors, shown within the colored rectangle, highlight the supply/demand relationship between the industries and the forecast/capacity relationship that influences the pace of their respective transitions. The bi-directional linkages between the transitions and their respective industries create a closed-loop system that strongly influences the systems' dynamic behavior. Socio-political and techno-economic pressures also influence dynamic behavior; for example, by geopolitical risks negatively influencing supply or pressure to reduce CO_2 emissions positively influencing forecasts. These pressures respond to industry and industry transition feedback and provide both positive and negative feedback to the primary coupling factors.

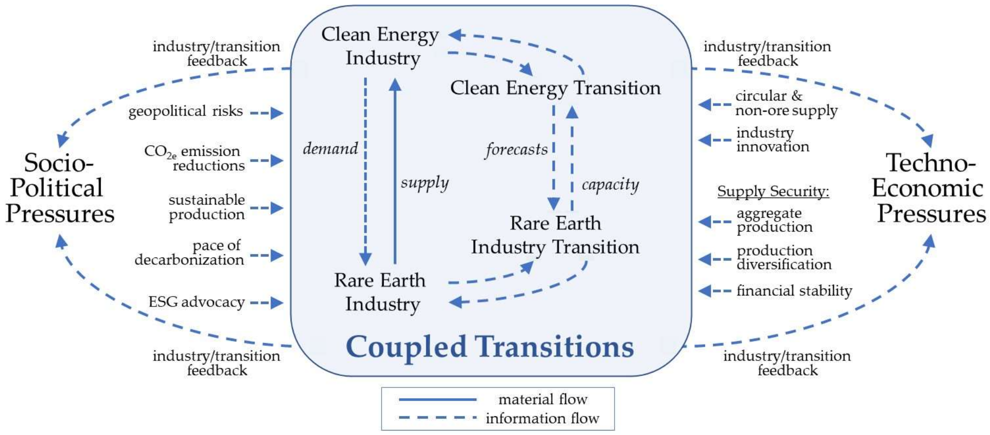

Figure 1. Conceptual coupled transition model showing exogenous pressures. Author's work, adapted from Vanek et al. (2016) and Verrier et al. (2022)) [4,5].

Other significant factors include:

- Market competitiveness: the rare earth market is highly concentrated in China, which dominates production, processing, and fabrication, including approximately 92% of permanent magnet fabrication. In addition, China imposes a 13% value-add tax (VAT) on all REEs that is rebated to Chinese firms, further reducing ex-China competitiveness. This near-monopoly control greatly reduces the commercial opportunities for REI firms in the MSPs and other nations.
- Import reliance: Related to a lack of market competitiveness, China's market control gives it the ability to establish production and export quotas that restrict supply and increase prices. As clean energy technology becomes increasingly critical to global energy decarbonization, the sensitivity to supply restrictions also increases.
- Substitution pressure: As part of industry innovation, R&D efforts to find substitutes for rare earth magnet metals have been underway for decades but with marginal success. Substitution R&D efforts to reduce supply security risk also include industry process and technology innovation, circular economy technology, and non-ore (primarily from coal and mine tailings) REE extraction.

Unilateral efforts to address the supply security challenges began in the wake of the 2010 market disruption, while coordinated bilateral and multinational efforts did not appear until the end of that decade. Plans to diversify supply away from China are being formulated and are expected to be in the range of billions of dollars. What is not part of the planning discussions is long-term planning for the industry to become profitable once stimulus funding is removed, as inevitably will happen.

By focusing on the REI transition, we intend to show a novel approach to developing transition strategies that address both the supply security challenges and the long-term stability of the REE industry.

2. Method

The method creates an exploratory model [6] of the REI based on an adaptation of Porter's diamond model theory of international competition [7] using the Ventity hybrid dynamic simulation software (version 2021) [8]. The full description of the method is contained in the author's dissertation (publication pending) [9].

Diamond model theory is a strategy framework that seeks to explain why some countries are successful in developing international competitive advantage and others are not. The unit of analysis is the national industry. To compete internationally, industries must first seek competitive advantage in their domestic or home nation. Success in the home nation prepares it to expand and be successful internationally.

As the diamond model is inherently a dynamic feedback network, it is well suited to study using dynamic feedback methods. Porter [10] encouraged the use of dynamic models to ensure logical consistency in the strategy framework, and vice-versa. Forrester [11], Sterman [12], and Morecroft [13] and others have described how dynamic simulation models can be applied to the study of strategy modeling. Cavana and Hughes [14], Kunc [15], and others have used dynamic simulation models to investigate Porter's strategy framework.

Figure 2 shows the original (a) and adapted (b) diamond model.

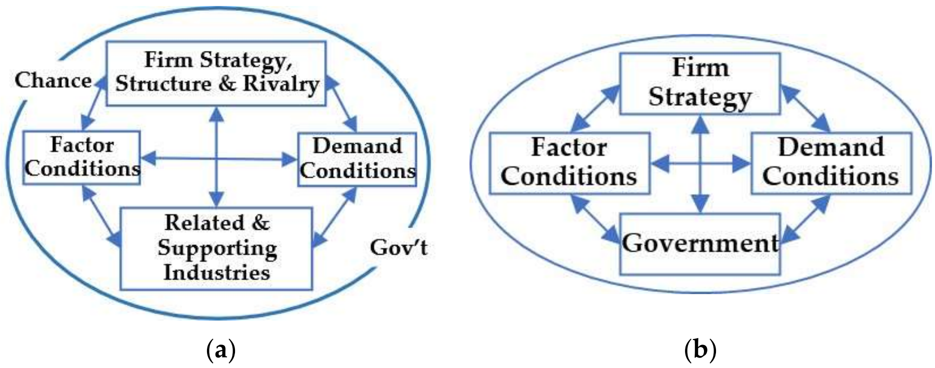

Figure 2. Porter's Diamond Model. (**a**) Original model. (**b**) Adapted model for the rare earth industry transition.

The original diamond model consists of four determinants and two additional variables. The four determinants, acting individually and dynamically, create the framework for building competitive advantage first at the national, and then international, level. The four determinants (Figure 2a) are:

- Firm Strategy, Structure, and Rivalry.
- Factor Conditions.
- Demand Conditions.
- Related and Supporting Industries.

The two additional variables—chance and government—play unique roles. Chance refers to events that are initiated outside the diamond model, disrupting some firms and enabling others. Chance events disrupt the otherwise orderly dynamics of the four determinants. Chance examples include R&D discoveries, supply chain disruptions, major policy adjustments, etc. The natural role of government is ideally that of an enabler of competitive advantage at the industry level, benefiting all firms in the national industry.

For our approach, we have adapted the original diamond (Figure 2b) to reflect the direct intervention of the government in providing funding and in multilateral collaboration at the multinational TG level. We recognize this is a sub-optimal structure, as Porter noted that direct government action in one or more determinants can favor selected firms and introduce market distortions that impact national competitive advantage. The adaptation reflects the multilateral approach to quickly improve production diversity.

For this exploratory model, firms are aggregated by trade group (TG). We define three TGs: China, which consists of China and Myanmar, Minerals Security Partnership (MSP), which consists of seventeen trade-aligned nations and nation groups, and Rest of the World (RoW) which consists of countries not included in the other two TGs.

The diamond model adaptations (2b) to accommodate TGs are:

- Firm Strategy in place of Firm Strategy, Structure, and Rivalry: focus on Firm Strategy.
- Related and Supporting Industries: included in Factor Conditions.
- Government: included as a determinant to reflect the need for direct industry stimulus funding to enable production diversification.

- Chance: Chance events are modeled as variables within the production stages of the simulation model.

Simulation models are an efficient way to create and test scenarios that "offer improved understanding and insight" in the assessment of strategic policy [16]. Research by Łatuszyńska [17] suggests that the hybrid dynamic model approach, which combines system dynamics [12] and agent-based modeling [18], can offer more detailed insights into problems in the fields of economics and business.

The causal loop diagram (CLD) in Figure 3 expands on the conceptual coupled transition model shown in Figure 1. CLDs are qualitative models that show the main feedback loops of the system. The CLD is used to identify four key performance indicators (KPIs)—t, wo each for tracking progress for supply security and stability and industry long-term stability. Supply security and stability are measured based on aggregate production and production diversification, while industry long-term stability is measured based on transition schedule and transition cost.

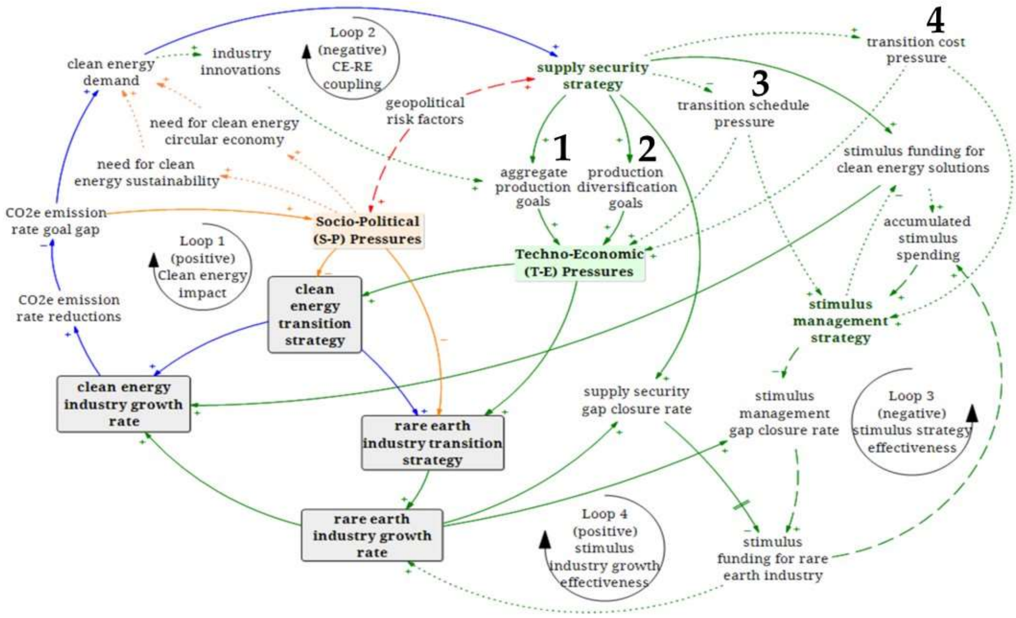

Figure 3. Causal loop diagram (CLD) from the conceptual coupled transition model of Figure 1. Green arrows refer to techno-economic pressures, orange arrows refer to socio-political pressures, blue arrows refer to clean energy transition, and the red arrows refer to geo-political risk factors.

All variables required for the KPIs are disaggregated to the TG level. Table 1 summarizes the key performance indicators (KPIs) used to measure transition progress.

Table 1. KPI definitions.

Action	KPI	Metric
1. Aggregate Production	Demand/supply gap	Measures the over/under supply of magnet metals at R4 Refining and over/under supply of permanent magnets at the F5 Fabrication stage.
2. Production Diversification	HHI [1]	Measures the HHI at M1 Mining (upstream), S3 Processing (midstream), and F5 Fabricating (downstream)
3. Transition Schedule	Stimulus Duration	Time period from first to last use of stimulus funding
4. Transition Cost	Stimulus Sum	Accumulated stimulus funding at M1 Mining (upstream), S3 Processing (midstream), and F5 Fabricating (downstream)

[1] HHI is calculated as $HHI = \sum_{i=1}^{n} s_i^2,\ where\ \sum_{i=1}^{n} s_i = 100$; where s = market share as an integer.

As the Rare Earth Industry Transition Dynamics (REITD) hybrid dynamic model is primarily concerned with clean energy, the model focus is the four magnet REEs. An overview of the essential model structure, known as a model map, is shown in Figure 4. The map shows the linkages between the entity types (white circles), which are the list of entities (agents), and the model logic for those entities. Entities with an entity type have a common set of attributes but different attribute values, for example, M1 Mining is defined as the entity type that contains all the mine entities in the model, C2 Production is the ore processing entity type, etc., Collections (green circles) are subsets of an entity type used for calculations, and analysis Actions and Triggers (orange triangles) are used to create, delete, or modify entity types based on the trigger logic. Entity types also contain the stock and flow logic from system dynamics to model entity behavior.

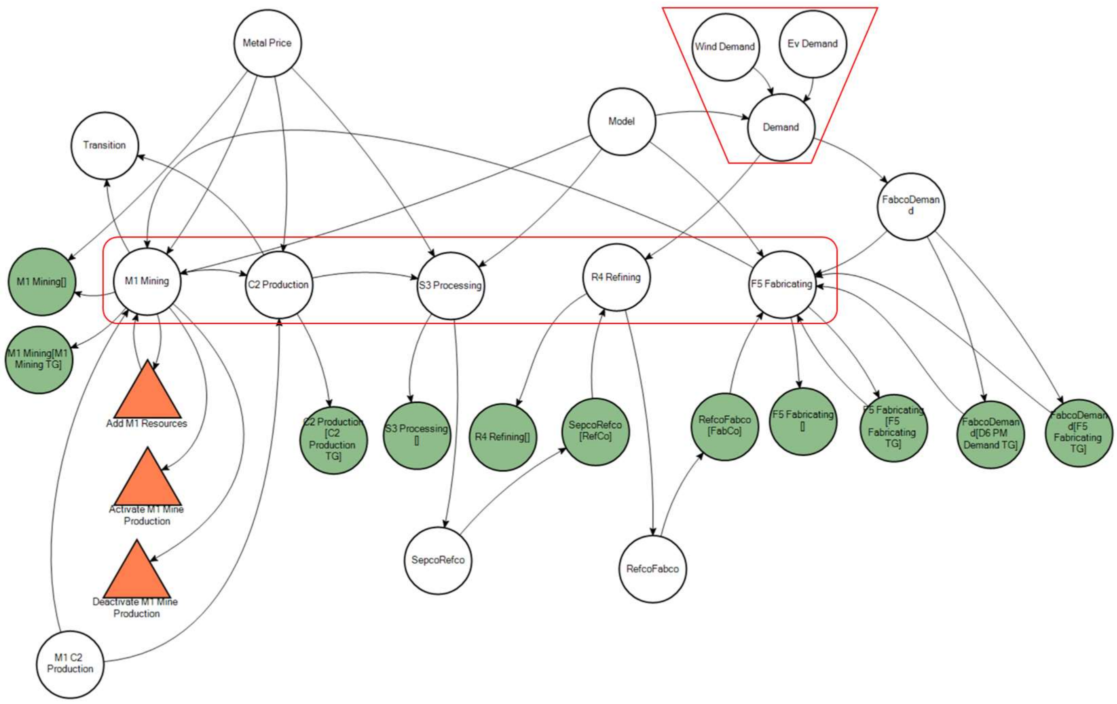

Figure 4. REITD hybrid dynamic simulation model map. The red polygon (top) highlights the demand entity types, the red rounded rectangle (middle) highlights the stages of production—upstream (M1 Mining and C2 Production), midstream (S3 Processing), and downstream (R4 Refining and f5 Fabrication).

Aggregated at the TG level, the Firm Strategy includes the metallurgical processing and magnet fabrication in the three mine-to-metal production stages. As shown in Figure 4, these are modeled as M1 Mining and C2 Production (Upstream), S3 Processing (Midstream), and R4 Refining and F5 Fabricating (Downstream) (boxed, middle). Clean energy demand for wind and electric vehicles (EV) is aggregated into permanent magnet demand in the Demand entity type, which is linked to both refining and fabricating production (boxed, upper right). The production/demand gap is fed back from F5 Fabricating to M1 Mining to adjust mining production. Upstream stages assume all mine production is to be processed.

Calculation of the four KPIs occurs at each time step (yearly) for the model simulation period from 2000 to 2050.

3. Results

The transition strategy scenarios listed in Table 2 were used to evaluate the approach.

Table 2. Transition strategy scenarios.

Variable	Base Case (BC)	Firm Strategy (FS)	Factor Conditions (FC)	Government (GV)	Multi-Determinant (MD)	Variable Effect
Stimulus share	20%	20%	20%	40%	40%	Stimulus share of new capacity investment
Initial capacity	M1: 1000/500 C2: 350/100 S3: 300/150	M1: 5250/1000 C2: 350/100 S3: 300/150	M1: 3500/1000 C2: 350/100 S3: 300/150	M1: 3500/1000 C2: 350/100 S3: 300/150	M1: 5250/1000 C2: 350/100 S3: 300/150	Time to first capacity expansion
Capacity adjustment fraction	M1: 40% C2: 50% S3: 50%	M1: 50% C2: 50% S3: 50%	M1: 40% C2: 50% S3: 50%	M1: 20% C2: 30% S3: 30%	M1: 40% C2: 50% S3: 50%	Time to next expansion vs. expansion cost
M1 Desired Mining	1.0 (no change from forecast)	1.05 (+5%)	1.1 (2030–2040)	1.0	1.1 (2030–2040)	Additional growth over baseline forecast (BAU)
Process Improvements	Upgrade ratio: 1.0 Mass pull: 1.0 Recovery: 1.0	Upgrade ratio: 1.0 Mass pull: 1.0 Recovery: 1.0	Upgrade ratio: 1.05 Mass pull: 1.05 Recovery: 1.005	Upgrade ratio: 1.05 Mass pull: 1.05 Recovery: 1.005	Upgrade ratio: 1.05 Mass pull: 1.05 Recovery: 1.005	Increase value
MSP Processing of China Imports	No change	No change	No change	S3: 20% R4: 20%	S3: 20% R4: 20%	Process 20% of China S3, R4

Results were collected for each of the five scenarios. All scenarios used historical data for the period 2000–2020. The Base Case (BC) uses parameters that reflect current industry projections to provide baseline results. Firm Strategy (FS) aggressively seeks to increase mine-to-magnet production. Factor Conditions (FC) consider actions based on industry innovation and circular economy supply. Government (GV) considers actions involving increased government intervention. Multi-Determinant (MD) combines actions from FS and GV to aggressively improve production diversity.

The Base Case supply security results for HHI and demand production gap indicate that the China TG will retain production dominance through to the end of the model period, while magnet metal demand will exceed supply after 2025. The long-term stability indicators show the need for stimulus funding continuing through to 2050. These results are consistent with industry projections. In plain language, 'business as usual' will not be sufficient to supplant the China TG from its industry-dominant position.

Neither the Firm Strategy nor the Factor Conditions scenarios show improvement over the Base Case. The Government scenario shows aggregate supply exceeding demand after 2035 but requiring significant increases in stimulus funding from 2025 to 2050.

The Multi-Determinant scenario achieves both short-term supply security and stability goals, with aggregate production exceeding demand after 2025 and production diversification HHI results showing competitive parity for the MSP TG with the China TG for upstream production after 2038 and significantly improved competitive position for the MSP TG in downstream processing around the same time period. Long-term industry stability is unchanged from previous scenarios, with large stimulus funding required through to 2050.

The encouraging results for the Multi-Determinant scenario assume that the MSP TG can broker a trade deal with the China TG to permit the MSP TG firms improved access to China TG markets. While this may seem unrealistic today, research from Bown and Clausing [19] provides a detailed analysis of how such trade cooperation could succeed.

Their 'Gets and Gives' approach outlines broad, balanced policy actions designed to normalize critical minerals trade and increase clean energy technology supply.

4. Conclusions

An exploratory simulation model of the global rare earth industry transition, based on the dynamic networks inherent in the diamond model for international competitive advantage, was shown to be promising, with limitations. Combining classic nonlinear system dynamics and agent-based approaches produced a hybrid simulation model suitable for an interdisciplinary transition study that combines systems engineering, socio-technical energy transition thinking, and diamond model competitive advantage theory. Using this model, we were able to compare rare earth mine-to-magnet production to permanent magnet demand for two clean energy technologies for five rare earth industry transition strategy scenarios.

Starting from a base case scenario, the next two scenarios implemented simple transition strategies that emphasized a single production determinant, while the last two were complex strategies involving both production determinants and the government determinant focused on inter-TG trade. Scenario results for the two simple strategies supported by industry studies forecast that transitions using simple strategies would likely not be successful within the model time frame from 2000 to 2050. While the complex strategies did not discover a 'home run' scenario, they did suggest that complex policy choices involving inter-TG negotiations could, by reducing transition costs and schedule, lower the overall cost of reestablishing a diversified rare earth industry with lower supply security risks while ultimately providing better long-term stability for the industry.

Having validated the interdisciplinary approach, future work centers around developing a more detailed explanatory model from this exploratory model. This requires model enhancements in three areas—improved mine-to-magnet production calculations using disaggregated data at all stages of the mine-to-metal production chain, additional socio-technical exogenous inputs, and more detailed network implementation of the four determinants in the adapted diamond model. The resulting explanatory model would be of great use to study, for example, the multi-determinant transition strategy using complex policy approaches as suggested by Bown and Clausing [19].

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Dataset available on request from the author.

Conflicts of Interest: The author declares no conflicts of interest.

References

1. Kruemmer, T. *Investing in the Rare Earth Elements A Run Through the Basics*; 121 Mining Investment: Hong Kong, China, 2023; Available online: https://giti.sg (accessed on 28 June 2023).
2. International Energy Agency. *Critical Minerals Market Review 2023*; IEA: Paris, France, 2023; Available online: https://www.iea.org/reports/critical-minerals-market-review-2023 (accessed on 11 July 2023).
3. Natural Resources Canada. *Government of Canada—Critical Minerals*; Natural Resources Canada: Ottawa, ON, Canada, 2021; Available online: https://www.nrcan.gc.ca/our-natural-resources/minerals-mining/critical-minerals/23414 (accessed on 29 July 2022).
4. Vanek, F.M.; Albright, L.D.; Angenent, L.T. *Energy Systems Engineering: Evaluation and Implementation*, 3rd ed.; McGraw Hill Education: New York, NY, USA, 2016.
5. Verrier, B.; Li, P.-H.; Pye, S.; Strachan, N. Incorporating social mechanisms in energy decarbonisation modelling. *Environ. Innov. Soc. Transit.* **2022**, *45*, 154–169. [CrossRef]
6. Homer, J.B. Why we iterate: Scientific modeling in theory and practice. *Syst. Dyn. Rev.* **1996**, *12*, 1–19. [CrossRef]
7. Porter, M.E. *The Competitive Advantage of Nations: With a New Introduction*; Free Press: New York, NY, USA, 1998.
8. Ventana Systems. Ventity—Simulation Software for Complex Systems [Business]; Jacobs Gate, MA, USA: 2021. Available online: https://ventity.biz/ (accessed on 5 May 2021).

9. Thibeault, A. A Study of the Global Rare Earth Industry Transition. Ph.D. Thesis, University of North Dakota, Grand Forks, ND, USA, 2023.
10. Porter, M.E. Towards a dynamic theory of strategy. *Strateg. Manag. J.* **1991**, *12*, 95–117. [CrossRef]
11. Forrester, J.W. *Industrial Dynamics*; Pegasus Communications, Inc.: Waltham, MA, USA, 1961; ISBN 1-883823-36-6.
12. Sterman, J.D. *Business Dynamics: Systems Thinking and Modeling for a Complex World*; Irwin/McGraw-Hill: Chicago, IL, USA, 2000.
13. Morecroft, J.D.W. *Strategic Modelling and Business Dynamics: A Feedback Systems Approach*, 2nd ed.; John Wiley and Sons Ltd.: Berlin/Heidelberg, Germany, 2015.
14. Cavana, R.Y.; Hughes, R.D. Strategic Modelling for Competitive Advantage. *Syst. Dyn.* **1995**, *95*, 2.
15. Kunc, M. Revisiting Porter's Generic Strategies for Competitive Environments Using System Dynamics. In *Computational Analysis of Firms' Organization and Strategic Behaviour*; Mollona, E., Ed.; Taylor & Francis Group: Abingdon, UK, 2010; pp. 152–170.
16. Dangerfield, B. The Proper Role for System Dynamics Models in the Process of Policy Making in Business and Government. In Proceedings of the 9th International Conference of the System Dynamics Society, Bangkok, Thailand, 27–30 August 1991; Available online: https://proceedings.systemdynamics.org/1991/proceed/ (accessed on 15 July 2023).
17. Łatuszyńska, M. Hybrid System Dynamics—Agent-Based Simulation for Research in Economics and Business. In *Experimental and Quantitative Methods in Contemporary Economics*; Nermend, K., Łatuszyńska, M., Eds.; Springer International Publishing: New York, NY, USA, 2020; pp. 229–248. [CrossRef]
18. Martín García, J. *Agent-Based Modeling and Simulation I Practical Guide to the Analysis of Complex Systems*; ATC-Innova: Málaga, Spain, 2021; Volume 1, ISBN 9798599111306.
19. Bown, C.P.; Clausing, K.A.; How Trade Cooperation by the United States, the European Union, and China Can Fight Climate Change. Peterson Institute for International Economics, Working Papers(23–8). 2023. Available online: https://www.piie.com/publications/working-papers/how-trade-cooperation-united-states-european-union-and-china-can-fight (accessed on 18 October 2023).