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Transportation Electrification

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Abstract
As the world reacts to climate change, reducing vehicle emissions through the adoption of electric vehicles (EVs) has become a global priority. While vehicles that operate on electricity may help reduce fossil fuel extraction, they still have a significant impact on the environment, particularly due to the lithium mining required to build their batteries. As with nearly any form of land-based extraction, lithium mining contributes to ecosystem degradation and disruption, increased risks to human health, and the theft of indigenous land, of which a majority of the world's energy transition minerals like lithium are located on.[1] This paper aims to explore the many variables that make up the EV transition system, particularly focusing on how policy, like the Inflation Reduction Act (IRA), cost and demand interact with lithium mining expansion and the battery recycling/ wastestream, which directly impacts justice, equity and indigenous rights. The creation of our model allowed us to test multiple scenarios and observe how the system reacts to shocks, and ultimately confirmed our hypothesis that policy incentives and decreasing EV costs contribute to expansion of lithium mining operations, which potentially could be mediated by investment in and expansion of lithium recycling capabilities. This study should serve to demonstrate the complexity of the transportation electrification system and a warning that while EVs may have significant benefits to the environment, they do not come without harms of their own which need to be balanced into the equation.

Introduction
Despite the long history of electric vehicles, modern electric cars have become popular again in the market after 1996, when the first modern mass-produced electric vehicle was invented in response to a California mandate that required automakers to have zero-emissions vehicles ready for market by 1998.[2] [3] The global electric vehicle market was valued at $163.01 billion in 2020, and is projected to reach $823.75 billion by 2030, registering a compound annual growth rate (CAGR) of 18.2% from 2021 to 2030.[4] Focusing on a smaller, national scale, the electric car sales in the United States increased from a mere 0.2 percent of total car sales in 2011 to 4.6 percent in 2021.[5]
An electric vehicle operates on electricity on an electric motor that requires constant supply of energy from a variety of batteries, including lithium ion, molten salt, zinc-air, and various

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[1] John R. Owen, Deanna Kemp, Alex M. Lechner et al. (2023.) Energy transition minerals and their intersection with land-connected peoples. Nat Sustain, 6:203–211. https://doi.org/10.1038/s41893-022-00994-6.
[2] (n.d.) How GM Beat Tesla to the First-True Mass-Market Electric Car. Wired. Retrieved on April 19, 2023 from https://www.wired.com/2016/01/gm-electric-car-chevy-bolt-mary-barra/#:~:text=In%201996%2C%20in%20response%20to,vehicle%20of%20the%20modern%20era.
[3] (n.d.) The History of the Electric Car. Department of Energy. Retrieved on April 19, 2023 from https://www.energy.gov/articles/history-electric-car#:~:text=Here%20in%20the%20U.S.%2C%20the,spark%20interest%20in%20electric%20vehicles.
[4] Akshay J, Sonia M. (Jan 2022.) Global Opportunity Analysis and Industry Forecast, 2021-2030. Allied Market Research. Retrieved on April 19, 2023 from https://www.alliedmarketresearch.com/electric-vehicle-market.
[5] Javier Colato and Lindsey Ice. (Feb 2023.) Charging into the Future: the transition to electric vehicles. U.S. Bureau of Labor Statistics. Retrieved on April 19, 2023 from https://www.bls.gov/opub/btn/volume-12/charging-into-the-future-the-transition-to-electric-vehicles.htm#:~:text=The%20market%20for%20electric%20vehicles,to%204.6%20percent%20in%202021.

nickel-based designs. Its benefits include reducing environmental pollution, providing higher fuel economy, low carbon emission and maintenance, convenience of charging at home, smoother drive, and reduced sound from the engine.[6] According to several public survey analysis results, these are the incentives that especially appeal to customers, and result in the fast growth of electric vehicles.[7]

Along with the fast-paced rise of electric vehicles in the market, we become more concerned about the social impacts it brings. In this project, we would like to examine the justice and equity issues from changes in the EV market within the U.S., and impacts from the amended relative policy programs to the EV market through research and simulations.

Research Question/Hypothesis

Problem Description

With the path to decarbonization paved with electrification, the United States is prioritizing the transition from combustion engine to electric vehicles (EV) through public policy.[8] The expected increase in demand for EVs will have cascading impacts including an increase in demand for rare earth metals, expansion of the electricity grid to meet consumer demand, and maturation of battery waste streams.[9]/[10] Through our system model, we hope to explore the equity and justice implications of public policy incentives allowing for the market of EVs to grow, increased consumer demand for EV products and derivatives, enhanced the needs of lithium in batteries, and boosted industry political influence for advocacy.

Hypothesis

The IRA incentivizes clean energy, electric vehicles, and electric homes by encouraging investments in green technologies, ramping up manufacturing and meeting the new demand. However, the effects of the new policy will not be obvious until at least one year after it is active because it takes time for the corporations and the public to update regulations and lifestyles that align with the new policies. The preparation for the end of the policy, on the contrary, keeps going on during the years of the act, and accommodations will be made right when the act ends. So the impacts on EV cost will start a couple of years after the IRA is launched, and end when it phases out. Used battery recycling contributes to environmental sustainability uncertainty, while maintenance and public budgeting draw financial and social sustainability interests. Humanity topics proposed in this dynamic system include justice/equity and indigenous rights which simultaneously push concerns of international sourcing of rare minerals to the table.

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[6] Ibid.

[7] Ibid

[8] (Aug 2021.) President Biden Announces Steps to Drive American Leadership Forward on Clean Cars and Trucks. The White House. https://www.whitehouse.gov/briefing-room/statements-releases/2021/08/05/fact-sheet-president-biden-announces-steps-to-drive-american-leadership-forward-on-clean-cars-and-trucks/.

[9] IEA. (2021.) The Role of Critical Minerals in Clean Energy Transitions. IEA, Paris https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions. License: CC BY 4.0.

[10] Hauke Engel, Russell Hensley, Stefan Knupfer, & Shivika Sahdev. (n.d.) How electric vehicles could change the load curve. McKinsey. Retrieved on February 7, 2023, from https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/the-potential-impact-of-electric-vehicles-on-global-energy-systems.

Method

Causal Loop Diagram (CLD)

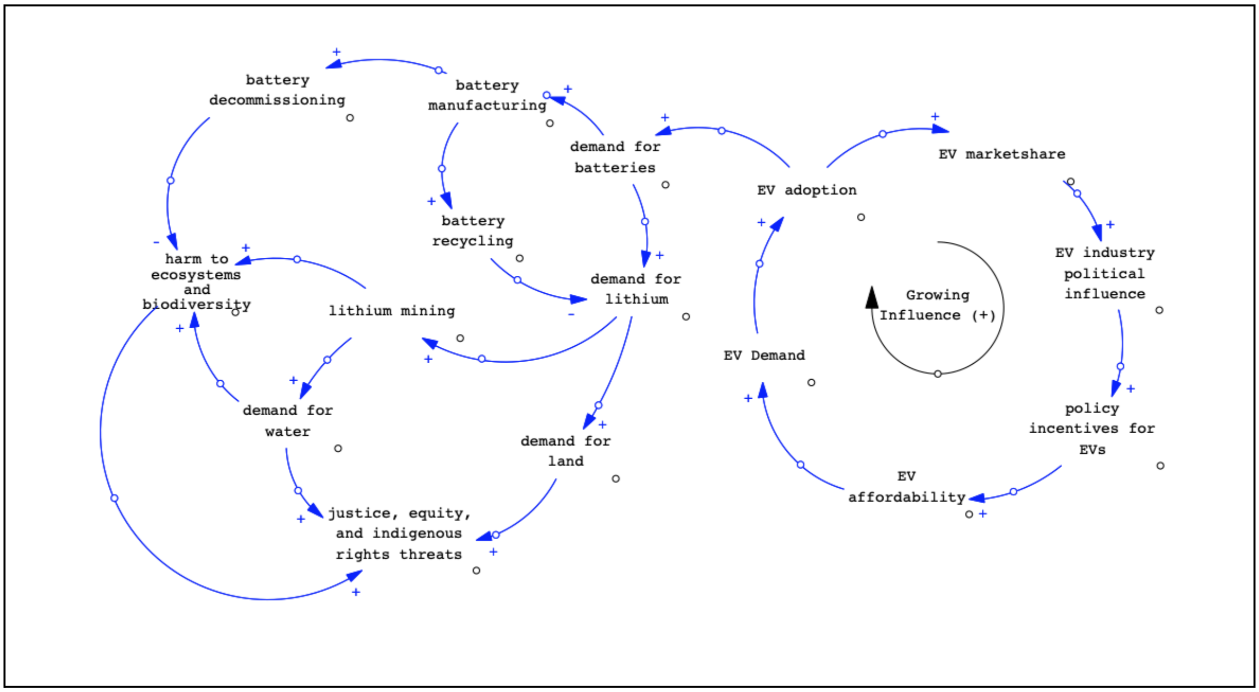

Figure 1. Causal Loop Diagram

This conceptual diagram shows the interactions between the growing demand for electric vehicles and the subsequent impact on the lithium industry. Visually separated, the political factors related to EV demand are on the right, and the effects of the lithium industry are on the left, with a connection between the spaces being that EVs require lithium batteries.

The political factors related to EV demand form a reinforcing loop; as EV adoption increases, the market share increases resulting in the EV industry having a more significant political influence. With this influence, there could be an increase in EV purchase incentives that make the vehicles more affordable and thus increase the demand and adoption of EVs.

There are no loops on the lithium side of the diagram; however, there are distinct regions of interactions. First is the battery waste stream space; demand for batteries influences the demand for lithium as well as battery manufacturing. The manufacturing then influences the maturation of the lithium recycling stream as more batteries are manufactured, more will eventually reach the end of life and need to be recycled. As the recycling waste stream matures, there will be less demand for mined lithium. Another distinct space is the environmental damage area where lithium mining increases the water demand, which can cause harm to ecosystems and biodiversity. Mining for lithium also increases the harm to ecosystems and biodiversity. The last distinct space is the justice space, where demand for lithium increases lithium mining, thus the demand for water and land. These each can increase justice, equity, and indigenous rights threats.

The CLD served as the basis for the formation of a fuzzy cognitive map (FCM) where positive or negative relationships between variables were mapped. Positive relationships indicate that as a variable increases so does

Stock and Flow Diagram

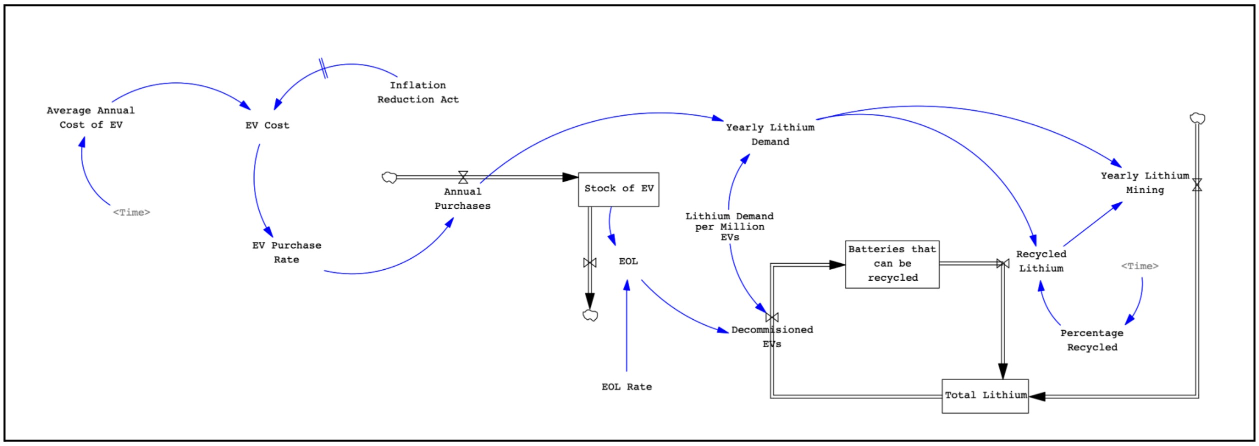

Figure 2. Stock and Flow Diagram

Based on the CLD, a stock and flow diagram was constructed to simulate the relationship between variables. To test the hypothesis, the model was constructed to determine how variables influence the stock of EVs, the number of batteries that can be recycled and the total amount of lithium used by the EV industry. The model starts in 2016 and runs until 2050. Starting from the top right side, the model depicts how a one year policy intervention in the form of a $7,500 tax credit[11] in the year 2023 would influence the cost of an EV. This policy intervention was chosen as it resembles the tax credit program from the Inflation Reduction Act (IRA). The initial value of an EV was $70,640[12] with a purchase rate based on historic trends of EV sales[2].

Year	Annual Purchases of EVs (millions) [2]
2016	0.15
2017	0.19
2018	0.35
2019	0.30
2020	0.32
2021	0.64

[11] Credits for New Clean Vehicles Purchased in 2023 or After. Internal Revenue Service. Retrieved on March 15, 2023, from https://www.irs.gov/credits-deductions/credits-for-new-clean-vehicles-purchased-in-2023-or-after.
[12] (n.d.) Electric Vehicles - United States. Statista. Retrieved on March 15, 2023, from https://www.statista.com/outlook/mmo/electric-vehicles/united-states#price.

Moving towards the lower left side of the diagram, the starting stock of EVs was .57 million vehicles[13] and the end of life rate is based on the average lifespan of an EV at 12 years[14]. The projected trend of the amount of lithium mined annually in kilotons (KT) is reflective of the one-year $7,500 subsidy that grew annual purchases and the projected increase in lithium recycling capacity at 6% every ten years[15]. The 2016 level of lithium demand of 77 KT is based on figures from the "Global EV Outlook 2020" report[16]. The amount of lithium per million electric vehicles is 8.8 kt[17].

Results

Cognitive Mapping Scenario Outputs

We use the MentalModeler system to help us test out our hypotheses on influences to variables in our model. The FCM is shown as Figure 3. It is transformed from the CLD and variables are categorized in colors. Briefly saying, the yellow variables focus on EV in the market; the orange ones are the manufacturing relative to batteries; the green variables are lithium-related ones.

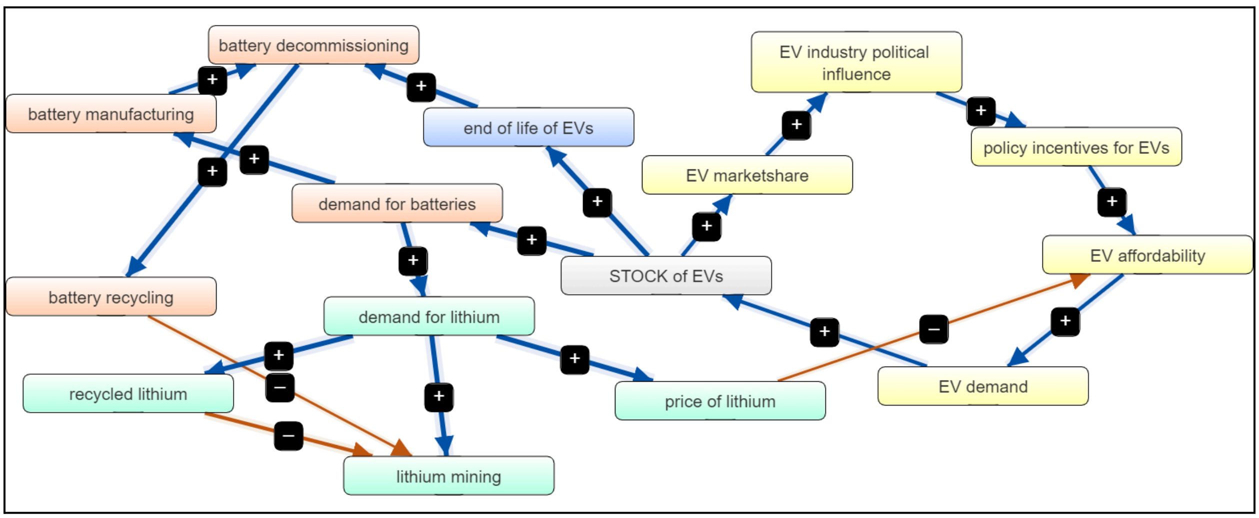

Figure 3. Fuzzy Cognitive Map (FCM)

1. Effect on EV demand as political influence decreases by 50%
   Our hypothesis states that increasing public policy initiatives (i.e., subsidies) to promote the EV market will increase EV demand. To explore the role of EV producers' political influence on public policy initiatives, we ran a scenario where their influence decreases by 50%. We chose to decrease influence by 50% as this is reflective of the current

[13] Ibid.
[14] Michael Samsu Koroma, Daniele Costa, Maeva Philippot, et al. (Jul 2022.) Life cycle assessment of battery electric vehicles: Implications of future electricity mix and different battery end-of-life management. Sci Total Environ, 831:154859. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9171403/.
[15] International Energy Agency. (June 2020.) Global EV Outlook 2020. Retrieved on March 13, 2023, from https://www.iea.org/reports/global-ev-outlook-2020.
[16] Ibid.
[17] Ian Shine. (Jul 2022.) The world needs 2 billion electric vehicles to get to net zero. But is there enough lithium to make all the batteries? World Economic Forum. Retrieved on March 5, 2023, from https://www.weforum.org/agenda/2022/07/electric-vehicles-world-enough-lithium-resources/.

instability of major EV producers like Tesla and Rivian, as showcased by workforce layoffs, while a 100% reduction in political influence was unrealistic.

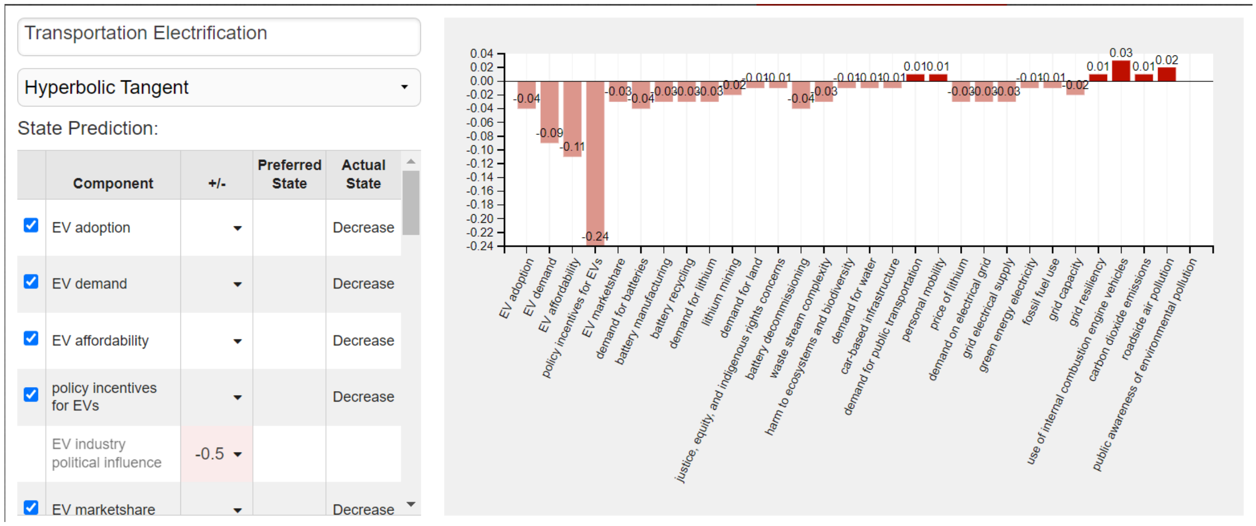

Figure 4. First FCM Scenario Test Result

This scenario resulted in a sharp decline in public policy initiatives that, in turn, decreased EV demand. EV adoption decreased a small amount and EV affordability also decreased a notable amount. Interestingly, the demand for internal combustion engine vehicles increased, but not to the same extent. Another interesting outcome from this scenario was that even though EV demand decreased a large amount, lithium mining only decreased a small amount.

2. Effect on justice, equity, and indigenous rights concerns as demand for lithium increases by 100%

   Our hypothesis also considers the social and environmental impacts of a growing demand for lithium. We chose to run this scenario as a 100% increase in demand as market projections expect lithium demand to increase by about this much over the next two decades[18].

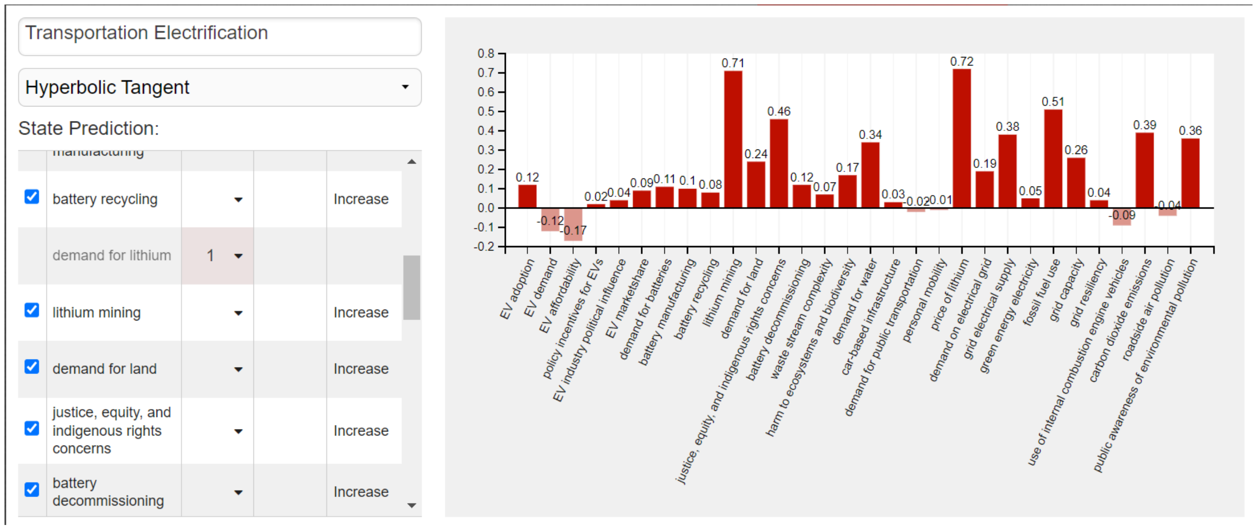

Figure 5. Second FCM Scenario Test Result

The results of this scenario shows that as the demand for lithium increases, the justice, equity, and indigenous rights concerns increase. An interesting result is as EV demand decreases, EV adoption increases. One could speculate that outside factors like more secondhand EVs entering the system could cause this, but this result is not congruent with our expectations and will have to be looked into further. In the future, it would be interesting to run a scenario where lithium demand increases while battery waste stream complexities decrease to understand how much recycling will need to occur for lithium mining to also decrease.

3. Effect on EV adoption as grid capacity decreases by 100%
We are interested in exploring the potential consequences of the electricity grid being damaged due to accidents such as explosions, and capacity rapidly decreasing. Setting the value of impact to 100% is extreme, as we were simulating damages that may require numeral years of recovery and repairment.

[18] International Energy Agency. (May 2021.) The Role of Critical Minerals in Clean Energy Transitions. World Energy Outlook Special Report. Retrieved on February 15, 2023, from https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions/executive-summary.

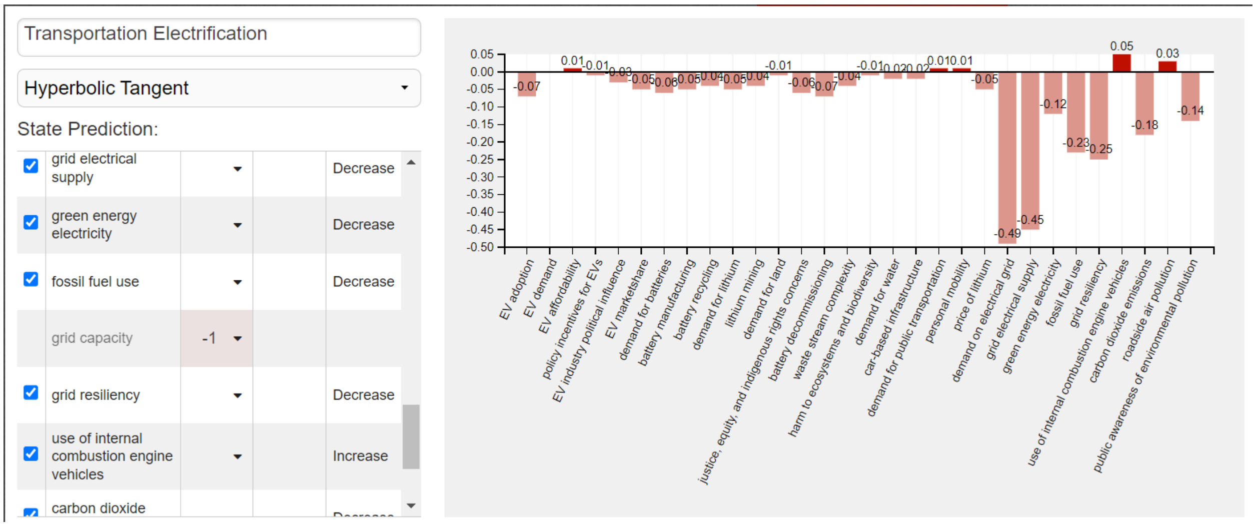

Figure 6. Third FCM Scenario Test Result

This large decrease in grid capacity caused a small decrease in EV adoption, but large decreases in grid supply and resiliency. It also produced a lot of interesting results, including as capacity decreased, so did demand on the grid. This seems counterintuitive as one would expect demand to remain the same even as capacity decreases. This result highlights the challenges of interpreting an FCM where no timescale is assigned. In the future, we should re-run this scenario over a variety of timescales to get a more accurate understanding of a rapid grid capacity decrease.

Nonlinearity

One nonlinear relationship identified was between policy intervention and the stock of EVs as the policy is only enacted for one year resulting in the stock of EVs increasing during 2023. Figure X exemplifies this as well as how the stock of EVs begins to reach equilibrium as the amount of EVs reaching end of life nears the amount of annual EV purchases.

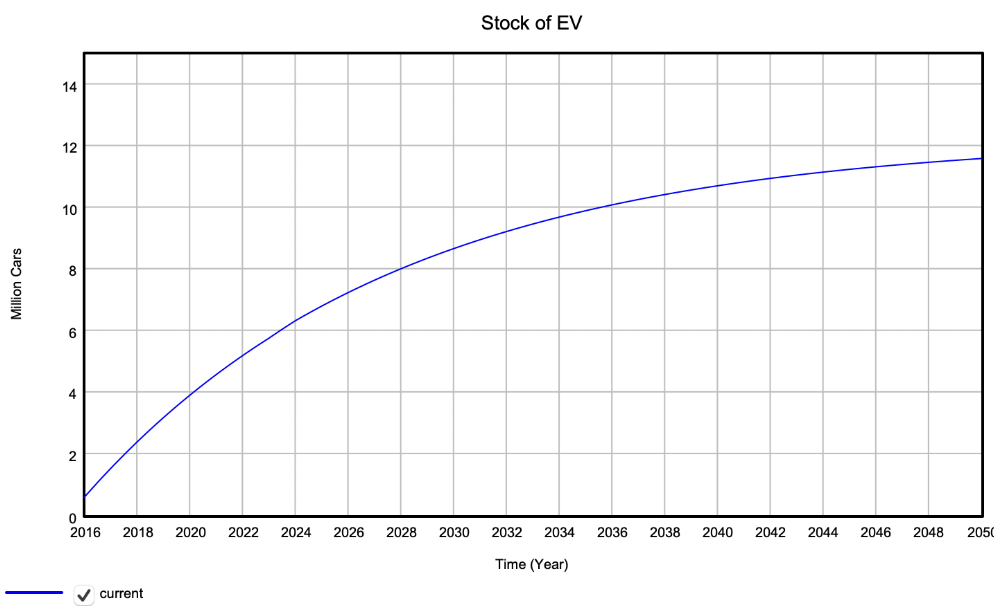

Figure 7. Stock of EVs from 2016 to 2050

The second nonlinear relationship identified was between total lithium demand and annual lithium mining as the model includes parameters that the recycling lithium waste stream will mature as more lithium batteries reach end of life. This will then decrease the amount of lithium required to be mined to keep with the demand of EV production.

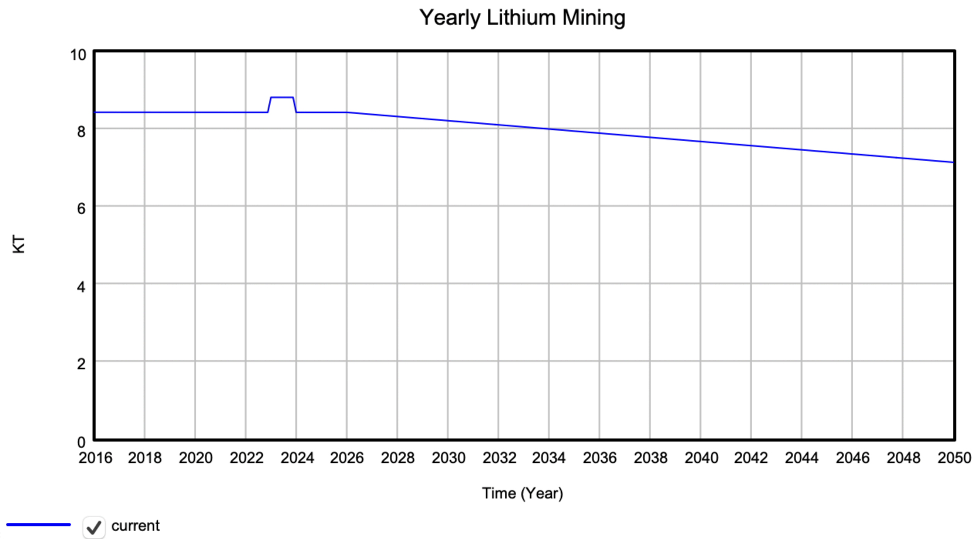

Figure 8. Amount of Lithium Mined Annually

Delays

A delay that was identified in our system is the impacts from policy incentives, as these are typically not seen right when the policy is enacted. We used this to explore how a policy incentive delay could impact EV cost, EV stock, recyclable batteries, and yearly lithium mining. We chose to model the Inflation Reduction Act (IRA), which was passed in 2022 and provides subsidies on EVs. A tax credit of $7,500 is given for passenger vehicles and will be in effect from 2023 to 2032.[19] Assumptions that were made in this model include the average annual cost of EVs will follow the trend of decreasing $410 every year past 2023, there will not be a policy incentive that takes over after the IRA is done in 2032, and it will take EV cost 2 years to form expectations on the IRA. Our model can be seen in the following stock and flow diagram (Figure 9) and the equations used for each variable are seen in appendix 1.

[19] Ibid.

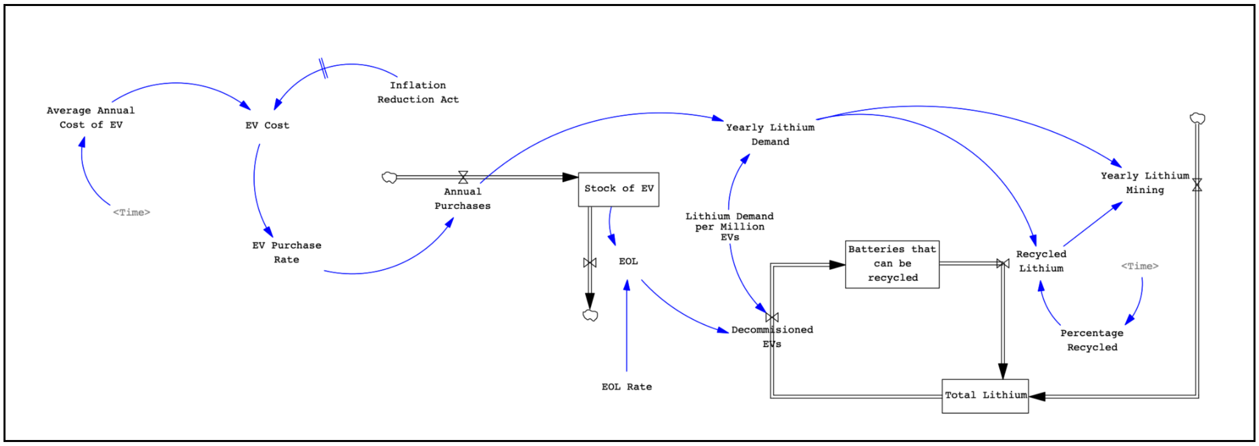

Figure 9. Stock and flow diagram for delay modeling

Variables Impacted by Delay

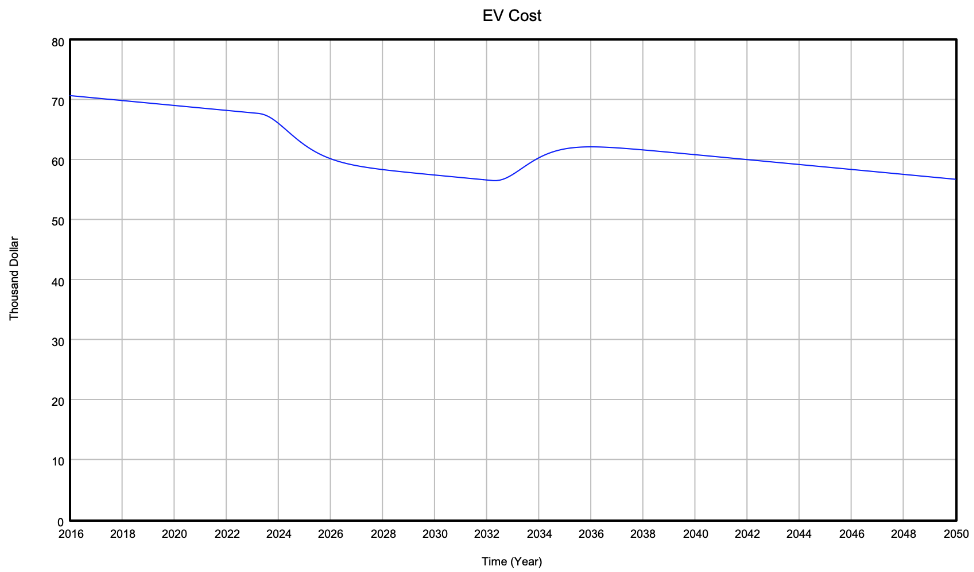

Figure 10. EV cost over time with delay

Figure 10 shows the cost of electric vehicles from 2016 to 2050. The general trend is of cost reduction with a sharp decline in 2023 due to the tax credit available for customers from the Inflation Reduction Act. EV purchases will be subsidized through 2032, after which the cost of EVs increases, but not to the pre-subsidy costs.

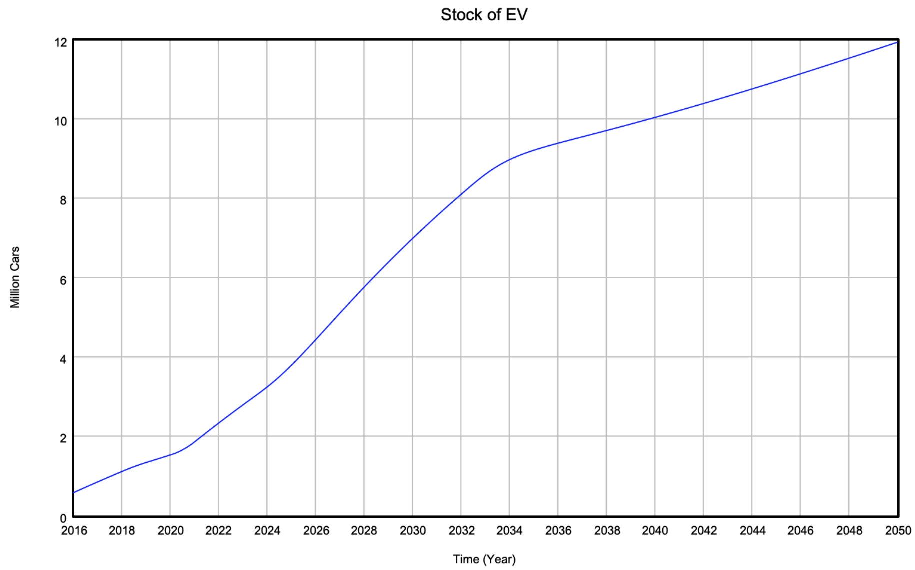

Figure 11. Stock of EVs over time with delay

The stock of EVs purchased by customers increases from 2016 through 2050 can be seen in Figure 11. The period of time in which consumers can apply for a EV tax credit (2023-2032) has the sharpest increase in vehicle stock. The increase in stock slows after the tax credit is no longer available and a larger number of EVs begin to reach their end of life and are decommissioned.

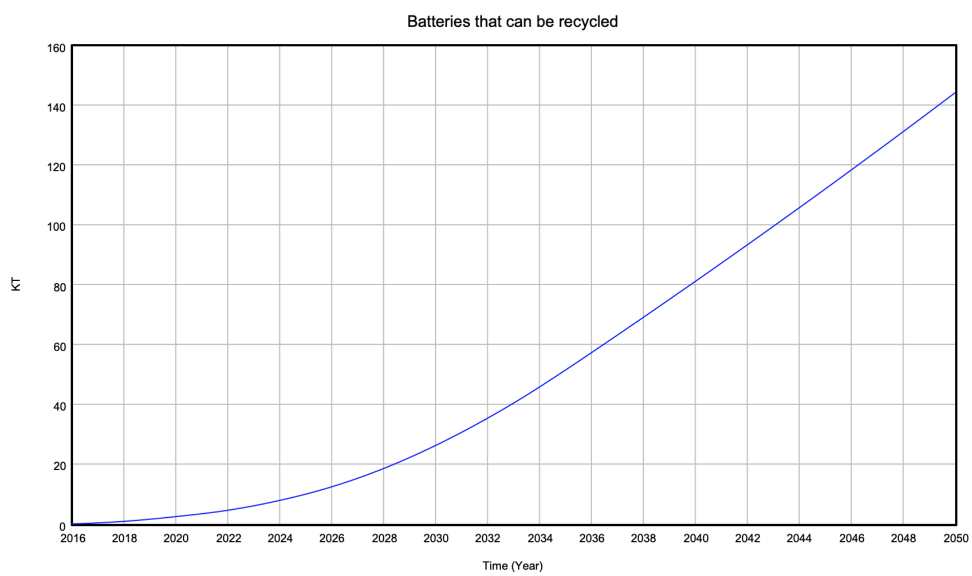

Figure 12. Batteries that can be recycled over time with delay

Assuming battery recycling technology improves, the kilotons of batteries that can be recycled increases exponentially through 2050. This result is heavily dependent on the assumption that recycling technology will improve and be widely available for all decommissioned EVs.

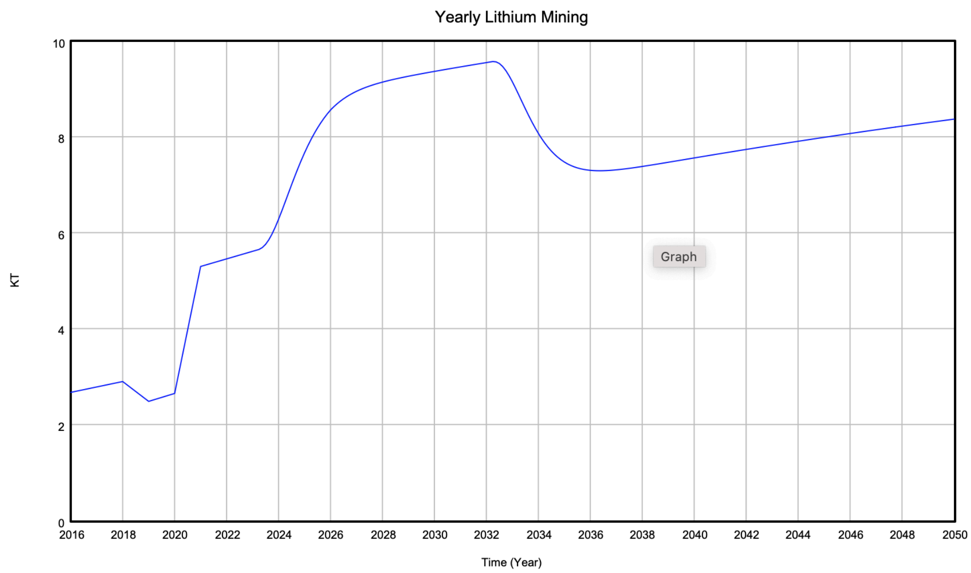

Figure 13. Yearly lithium mining over time with delay

The amount of lithium mined per year is dependent on the amount of EVs sold per year and the ability to recycle lithium batteries from decommissioned EVs. Before battery recycling technology improves, the amount of lithium mined per year increases with the exception of 2018-2019. As the technology for battery recycling improves, there is less demand for lithium mining as seen in the sharp decrease between 2032 and 2036. It is interesting to note that the model predicts that recycled lithium will not be able to meet the total lithium demand and that mining will increase steadily from 2036 to 2050.

Sensitivity Analysis

We tested the sensitivity of our model for 3 different variables, the length of the policy intervention, the rate of recycled lithium, and the cost of EVs. For each of these, we looked at the effect on yearly lithium mining.

Figure 14 shows the amount of lithium mined every year in scenarios of one, five and ten years of the EV rebate policy. All scenarios return to equilibrium after the policy duration, which indicates a low sensitivity. Figure 15 shows the impact of increasing recycling rates of lithium, which was modeled through a 1% and 2% increase in recycling every year starting from 2016. Both scenarios significantly decreased the yearly demand for new lithium and dramatically changed the equilibrium, showing the model is very sensitive to this variable. Figure 16 shows the impact of decreasing costs of EVs, modeled by reducing prices by 1 and 2% every year in addition to the current policy intervention. This scenario had the most significant impact on lithium mining, increasing the demand for lithium dramatically and demonstrating the high sensitivity our model has to this variable. Out of the variables we tested, the most likely to have the biggest impact on our system and lithium mining in particular is EV cost.

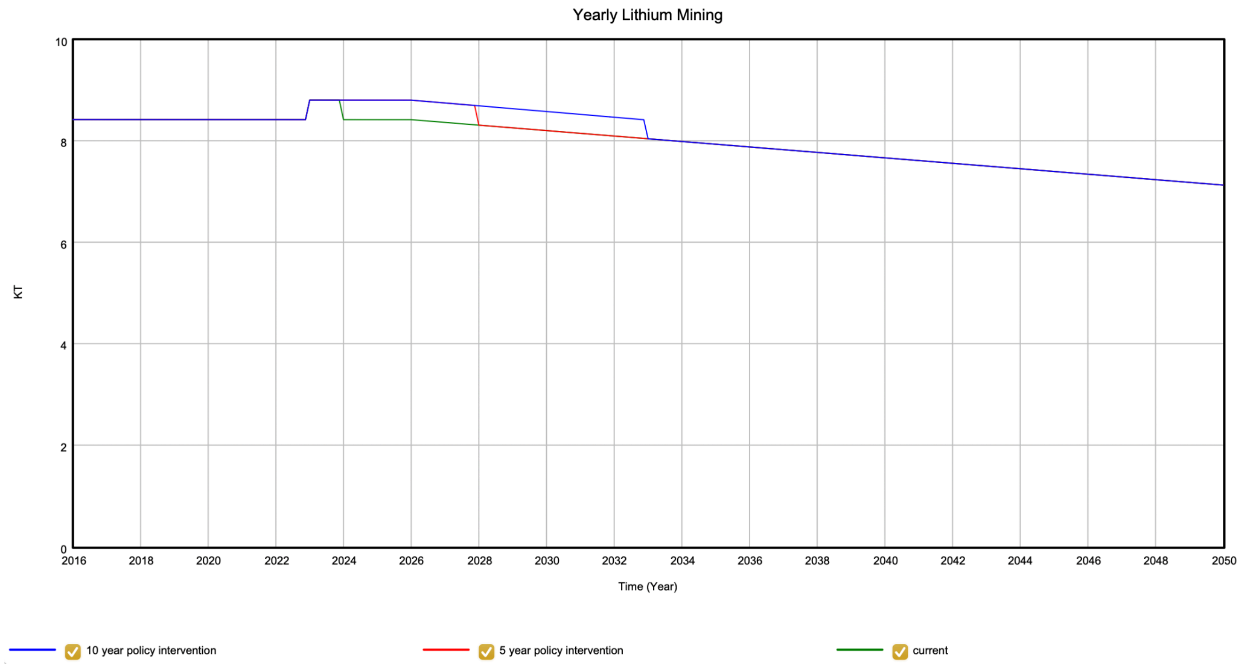

Figure 14. The sensitivity of yearly lithium mining to policy duration

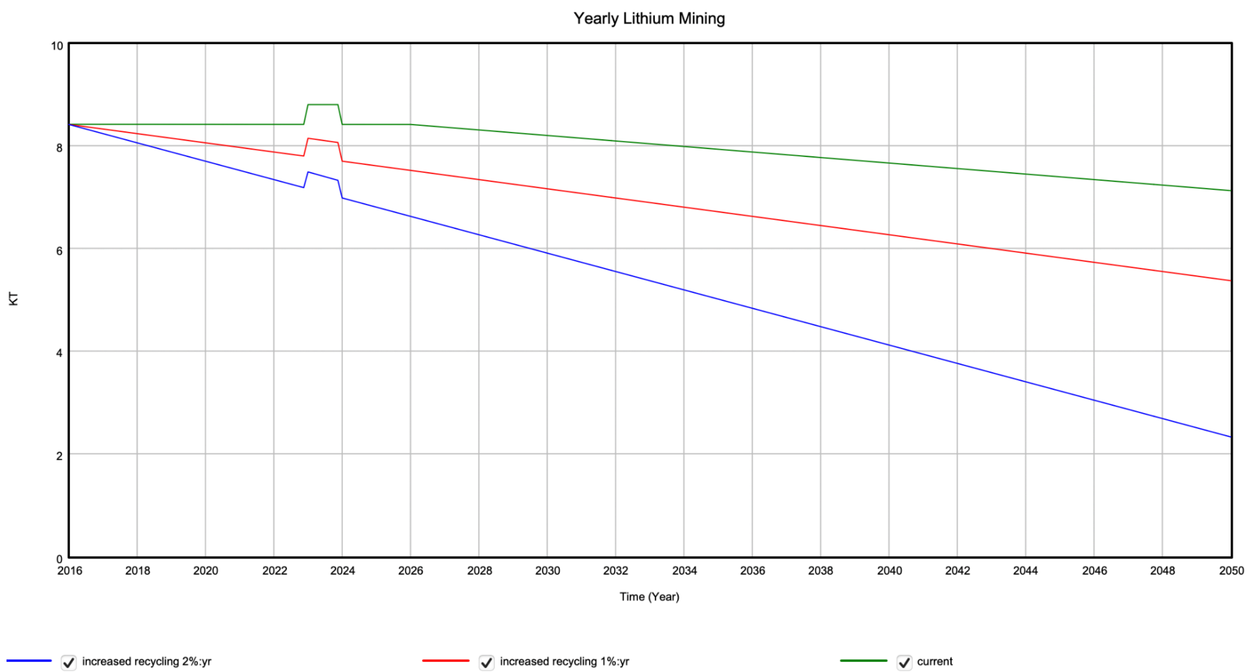

Figure 15. The sensitivity of yearly lithium mining to increased recycling rates

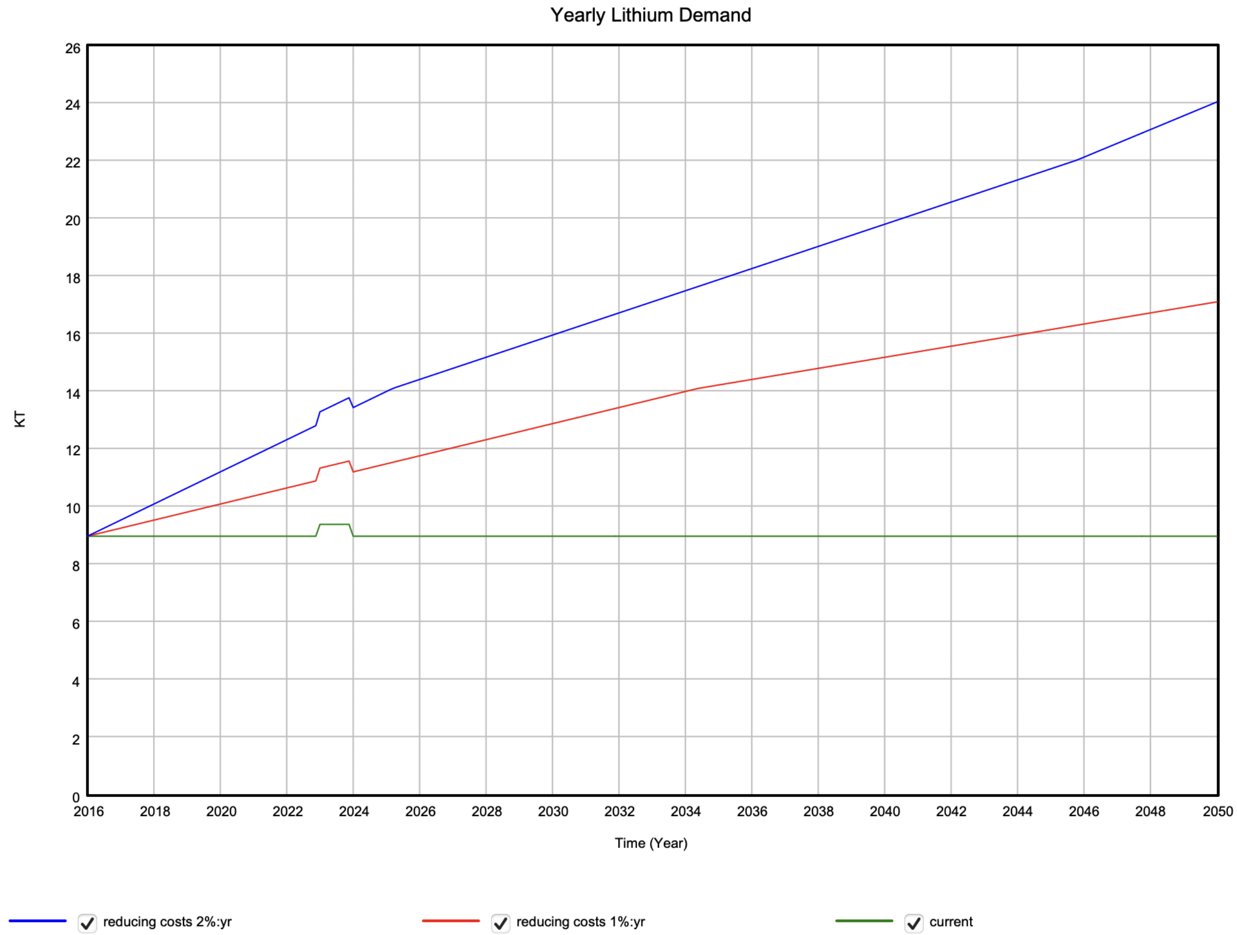

Figure 16. The sensitivity of yearly lithium mining to reducing EV costs

Conclusion

Though building out a simplified model of the main variables of transportation electrification, identifying connections, areas of nonlinearity, delays, and sensitivity, we were about to gain a strong understanding of our system's dynamics. Ultimately we identified EV cost as having the biggest individual impact on expansion of lithium mining, with the efficiency of lithium recycling being a key variable that could moderate this demand by keeping lithium within the system without additional mining. This study demonstrates the impact of increased EV adoption on environmental justice, as lithium mining is inseparable from its impacts on ecosystems, human health, and connections to indigenous lands. It's essential that these impacts are analyzed appropriately and that measures are taken to ensure that the energy transition doesn't further repeat the patterns of extraction and exploitation that initially resulted in the climate crisis that electrification seeks to respond to.

Appendix

Appendix 1. Equations and data used for delay and nonlinearity modeling

Equations:

- **Average Annual Cost of EV:** WITH LOOKUP (Time) ([(0,0)-(3000,80)],(2016,70.64),(2020,69),(2024,67.36),(2028,65.72),(2032,64.08),(2036,62.44),(2040,60.8),(2044,59.16),(2048,57.52),(2050,56.7))
    - Source: https://www.statista.com/outlook/mmo/electric-vehicles/united-states#price
- **Inflation Reduction Act:** 7.5*PULSE(2023,9) *Thousand Dollars*
    - Source: https://www.irs.gov/credits-deductions/credits-for-new-clean-vehicles-purchased-in-2023-or-after
- **EV Cost:** Average Annual Cost of EV-SMOOTH3(Inflation Reduction Act,2) *Thousand Dollars*
- **EV Purchase Rate:** WITH LOOKUP (EV Cost) ([(0,0)-(100,4)],(0,3.3),(20,2.5),(48,1.6),(68.59,0.64),(69,0.32),(69.41,0.3),(69.82,0.35),(80,0.01),(100,0))
- **Annual Purchases:** EV Purchase Rate
- **Stock of EV:** Annual Purchases-EOL *Million Cars*
- **EOL:** EOL Rate*Stock of EV
- **EOL Rate:** 0.083
- **Decommissioned EVs:** EOL*Lithium Demand per Million EVs
- **Lithium Demand per Million EVs:** 8.8 *KT*
- **Yearly Lithium Demand:** Annual Purchases*Lithium Demand per Million EVs *KT*
- **Batteries That Can Be Recycled:** Decommissioned EVs-Recycled Lithium *KT*
- **Total Lithium:** Recycled Lithium+Yearly Lithium Mining-Decommisioned EVs *KT*, initial value of 77
- **Yearly Lithium Mining:** Yearly Lithium Demand-Recycled Lithium *KT*
- **Recycled Lithium:** Percentage Recycled*Yearly Lithium Demand
- **Percentage Recycled:** WITH LOOKUP (Time) ([(0,0)-(50,10)],(0,0),(2026,0.06),(2036,0.12),(2046,0.18),(2056,0.24),(2066,0.3))

Data and Sources:

- Assumption that drivers are switching from Internal Combustion Engine Vehicles (ICE) to EV
    - Not purchasing an EV without retiring an ICE
- Stock of fully electric vehicles in the US as of 2021= 1.3 million

Year	New EV Sales (millions)	Stock of EV (millions)
2016	0.15	0.57
2017	0.19	0.76
2018	0.35	1.11

2019	0.30	1.41
2020	0.32	1.73
2021	0.64	2.37
2022	0.77	3.14
2023	0.95	4.09
2024	1.16	5.25
2025	1.42	6.67
2026	1.74	8.41
2027	2.13	10.54

  - Source: https://www.statista.com/outlook/mmo/electric-vehicles/united-states#unit-sales
  - https://www.iea.org/reports/global-ev-outlook-2020
- Stock of ICE light duty vehicles as of 2021= 118.074303 million
  - Source: https://www.eia.gov/opendata/v1/qb.php?category=2118520&sdid=AEO.2016.HIGHMACRO.ECI_STK_TRN_CAR_CNV_NA_NA_MILL.A
- Tax credit =$7,500
  - Source: https://www.irs.gov/credits-deductions/credits-for-new-clean-vehicles-purchased-in-2023-or-after
- Average Cost of EV in 2021

Year	**Cost (thousands)**	**Annual Purchase (millions)**
2016	70.64	0.15
2017	70.23	0.19
2018	69.82	0.35
2019	69.41	0.30
2020	69	0.32
2021	68.59	0.64

  - Source: https://www.statista.com/outlook/mmo/electric-vehicles/united-states#price
- Lifespan of EV= 12 years
  - Source: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9171403/

Lithium Demand and EV Demand Non-Linearity

- Lithium Demand

Year	Demand (Thousand Metric Tons)
2019	263
2020	327
2021*	465
2022	559
2023	685
2024	838
2025	1,003
2026	1,169
2027	1,349
2028	1,560
2029	1,831
2030	2,114

  - Source: https://www.statista.com/statistics/452025/projected-total-demand-for-lithium-globally/
- Unit Sales

Year	EV Sales (millions)
2016	0.15
2017	0.19
2018	0.35
2019	0.30
2020	0.32
2021	0.64
2022	0.77
2023	0.95
2024	1.16
2025	1.42
2026	1.74
2027	2.13

  - Source: https://www.statista.com/outlook/mmo/electric-vehicles/united-states#unit-sales