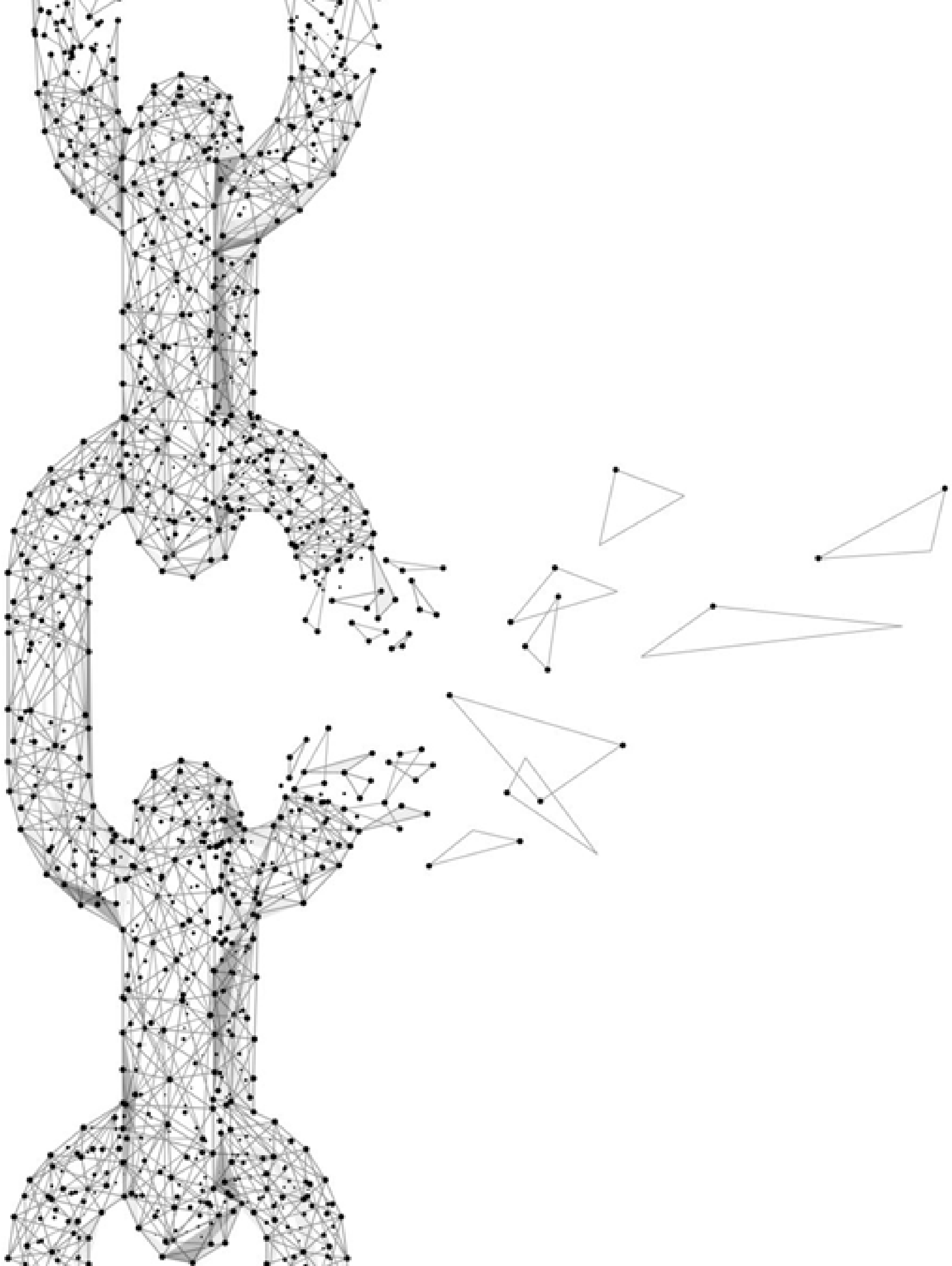
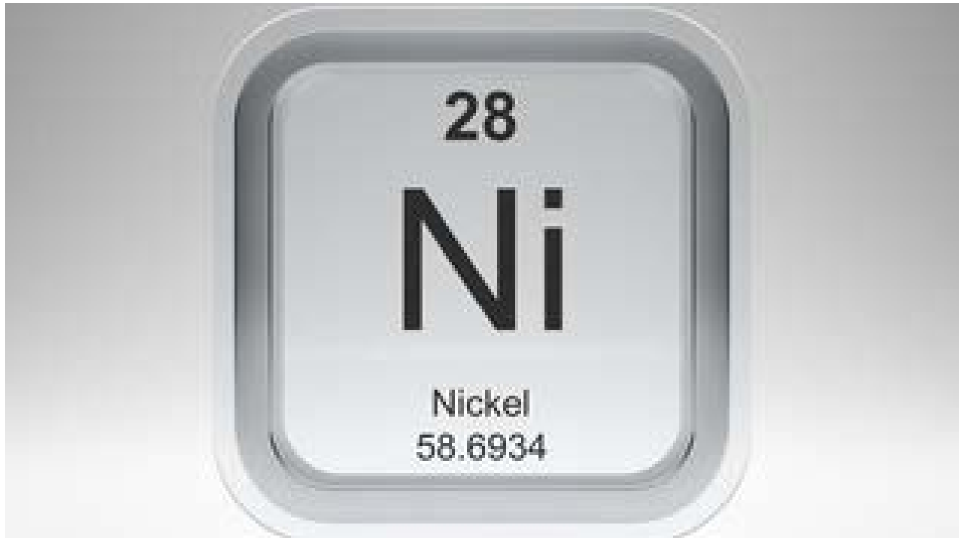


Modelling Metal Supply Chain Resilience

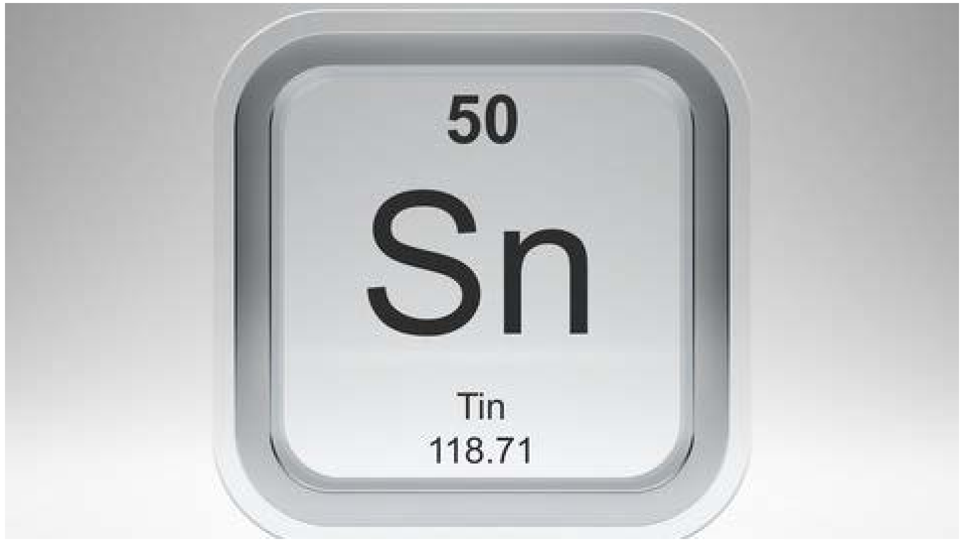
A Case Study of Nickel and Tin

Jessie Bradley
5/04/2022

TU Delft

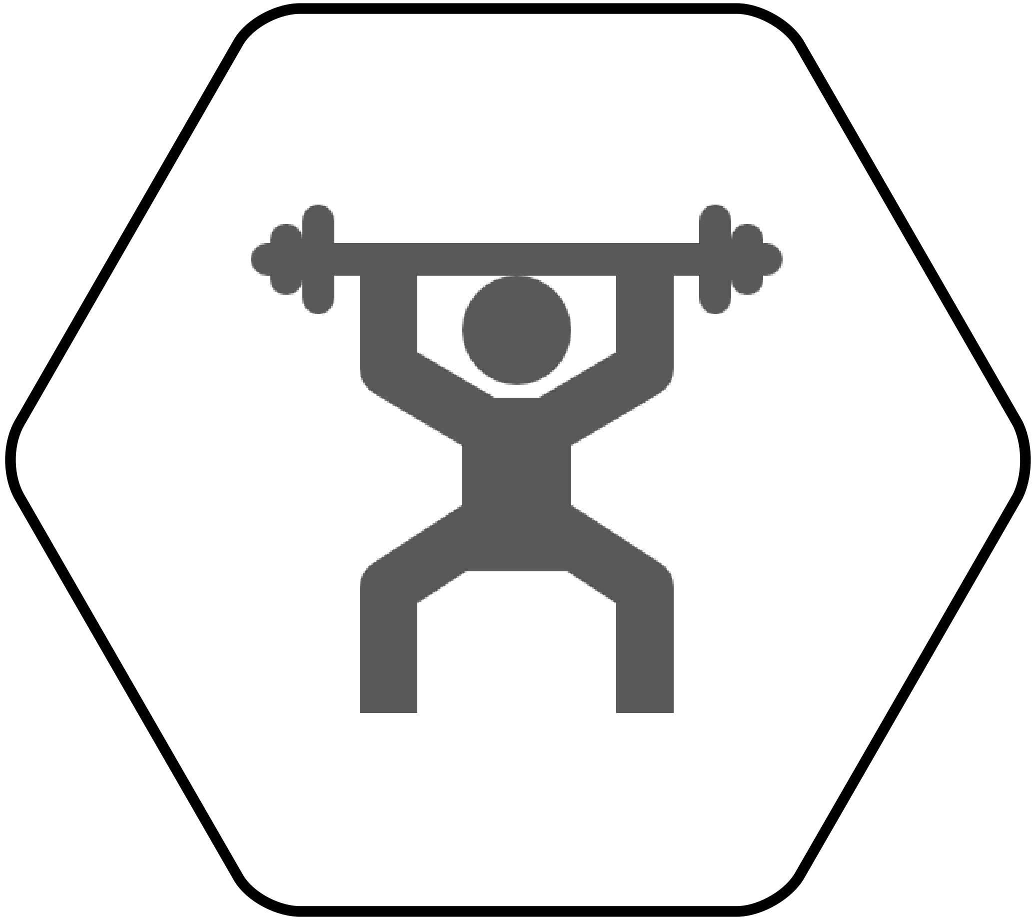


Recent developments



source: tradingeconomics.com

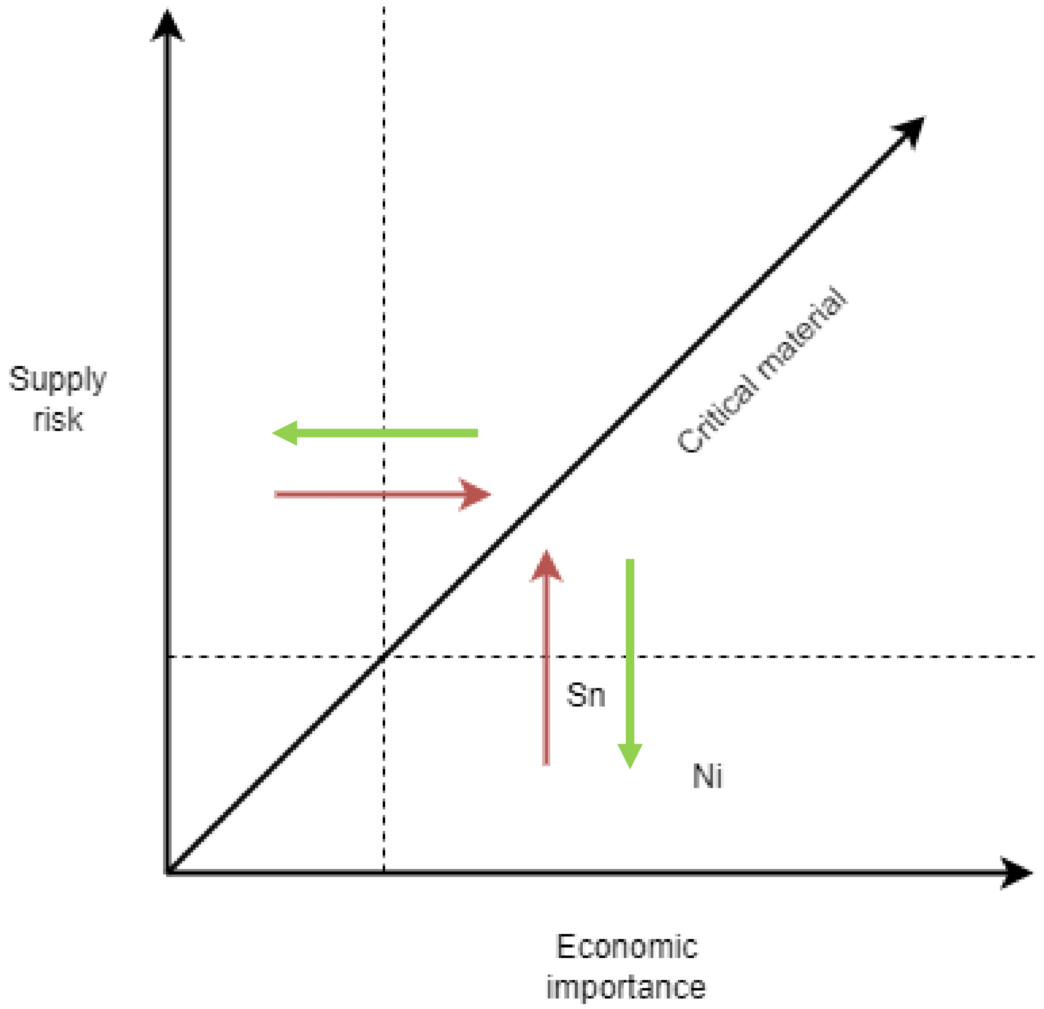
Supply Chain Resilience



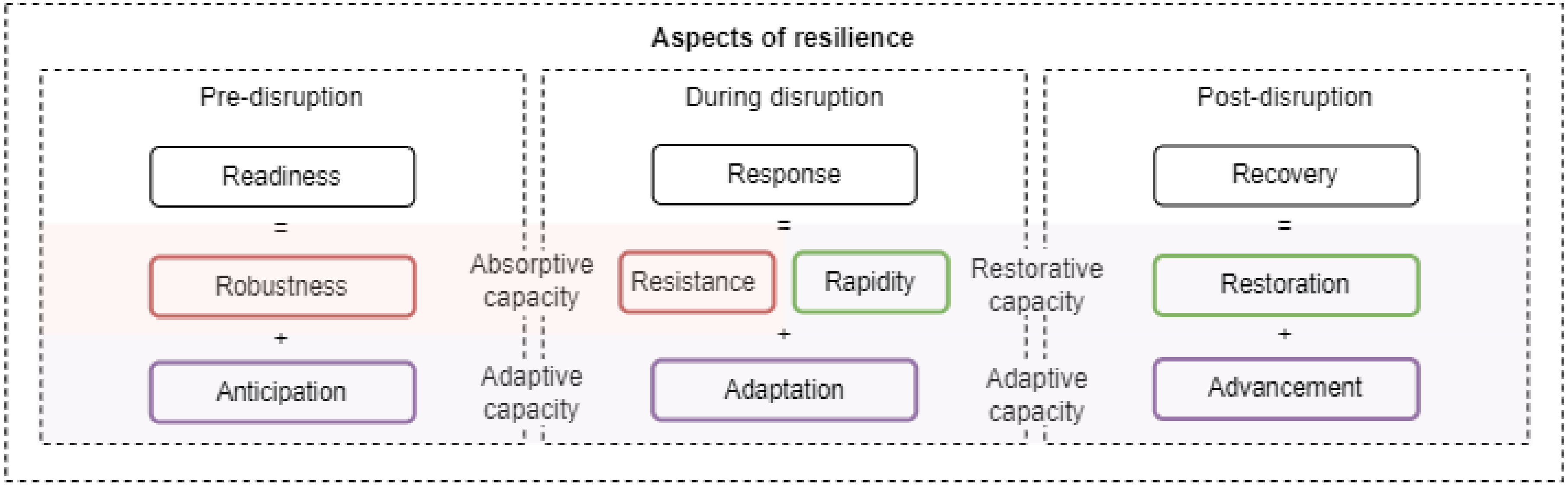
Material criticality

- High economic importance
- High supply risk
- Criticality is dynamic
- Ni and Sn *currently* not considered critical by European Commission
- Criticality highlights the problem
- Act before it becomes a problem

Solution: Supply Chain Resilience



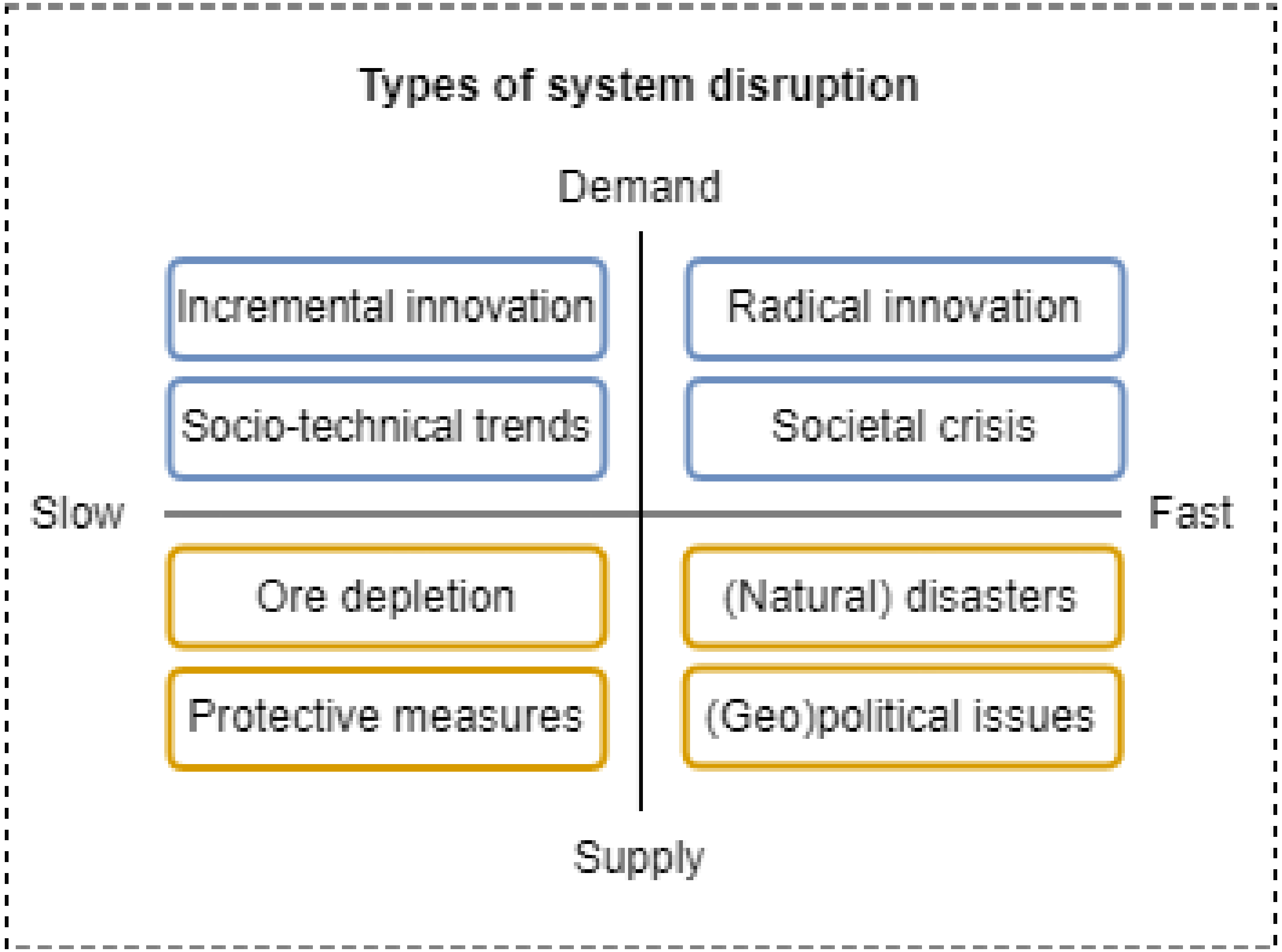
Supply Chain Resilience



'The capacity to supply enough of a given material to satisfy the demands of society, and to provide suitable alternatives if insufficient supply is available' (Sprecher et al., 2015, p.2).

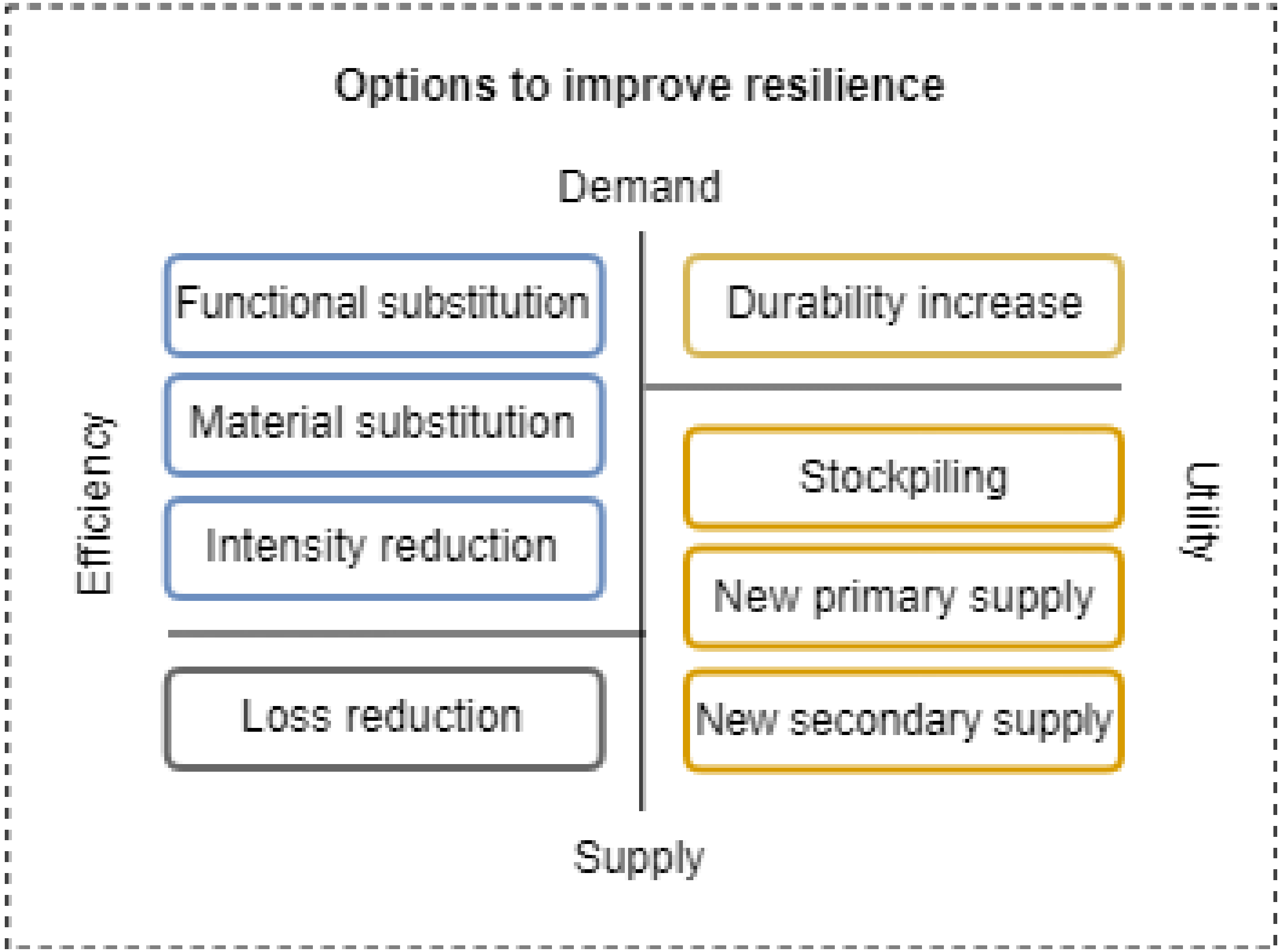
Disruptions





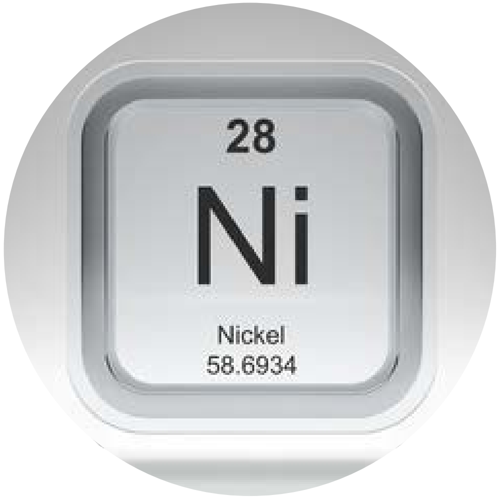


Resilience mechanisms



Supply Chain Modelling

Research goals



Nickel research:

Exploration of the development and resilience of the global nickel supply chain under various disruption scenarios, resilience mechanisms and other uncertainties between 2015 & 2060

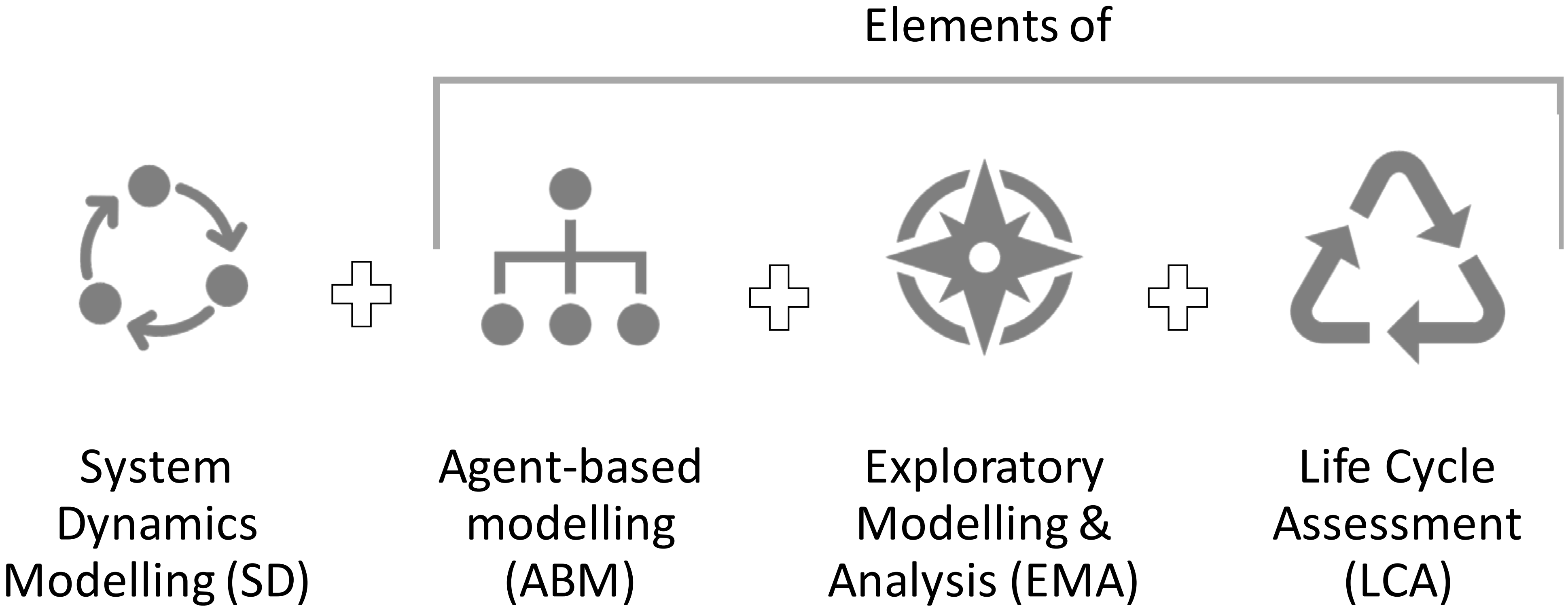
Status: ready for publishing

Tin research:

Exploration of the development and resilience of the tin supply chain and the impact of regional circularity policies at the global, EU28 and NL levels between 2017 & 2070

Status: developing model

Methodology



Novel aspects

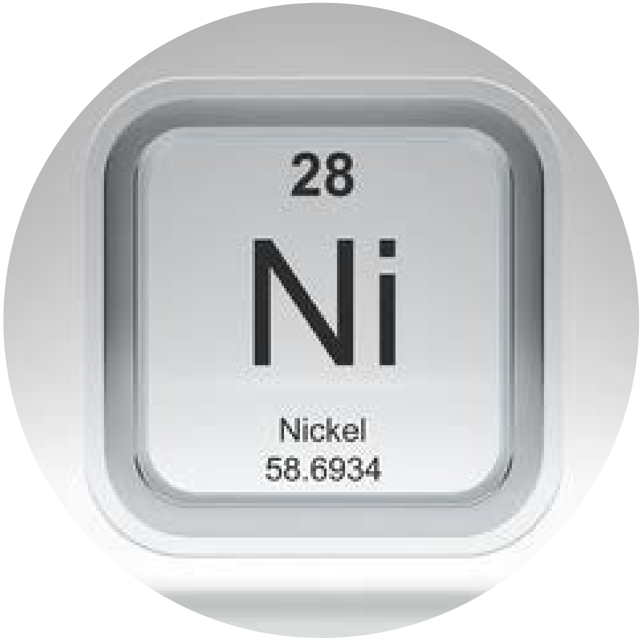
Nickel model:

Detailed primary supply structure at the level of individual mines

Tin model:

Regional demand, supply and trade between 8 regions

Nickel Model & Scenarios



Model structure (4 sub models)

Demand

Supply

Price

Impacts

Nickel model structure

Demand

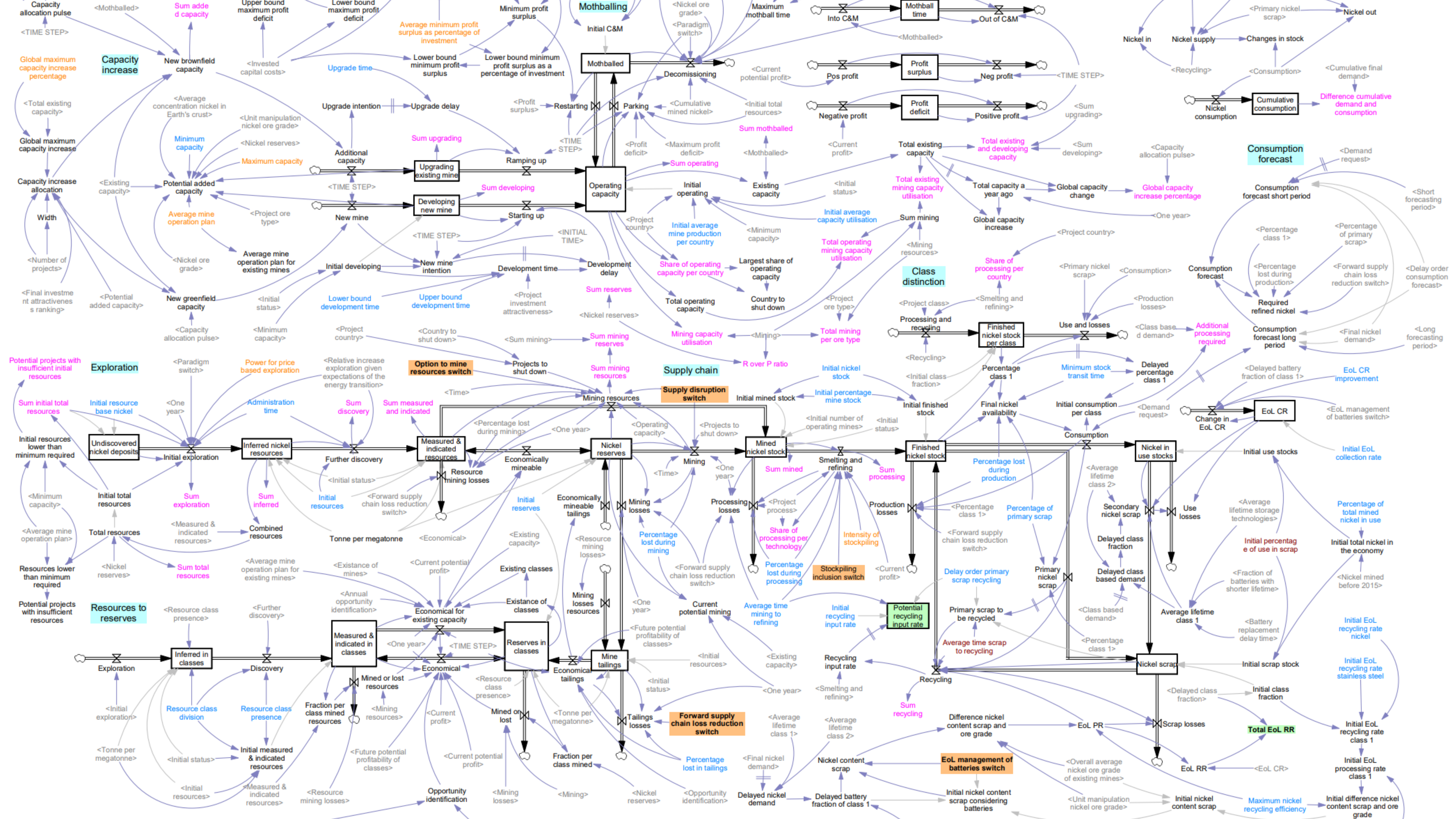
- Bottom-up: electricity generation, electricity storage, vehicles
- Top-down: Rest of the Economy (RoE)
- 3 uses (sectors): class I (batteries and other), class II (stainless steel)
- Price feedbacks included (substitution, price elasticity, intensity changes)

Supply

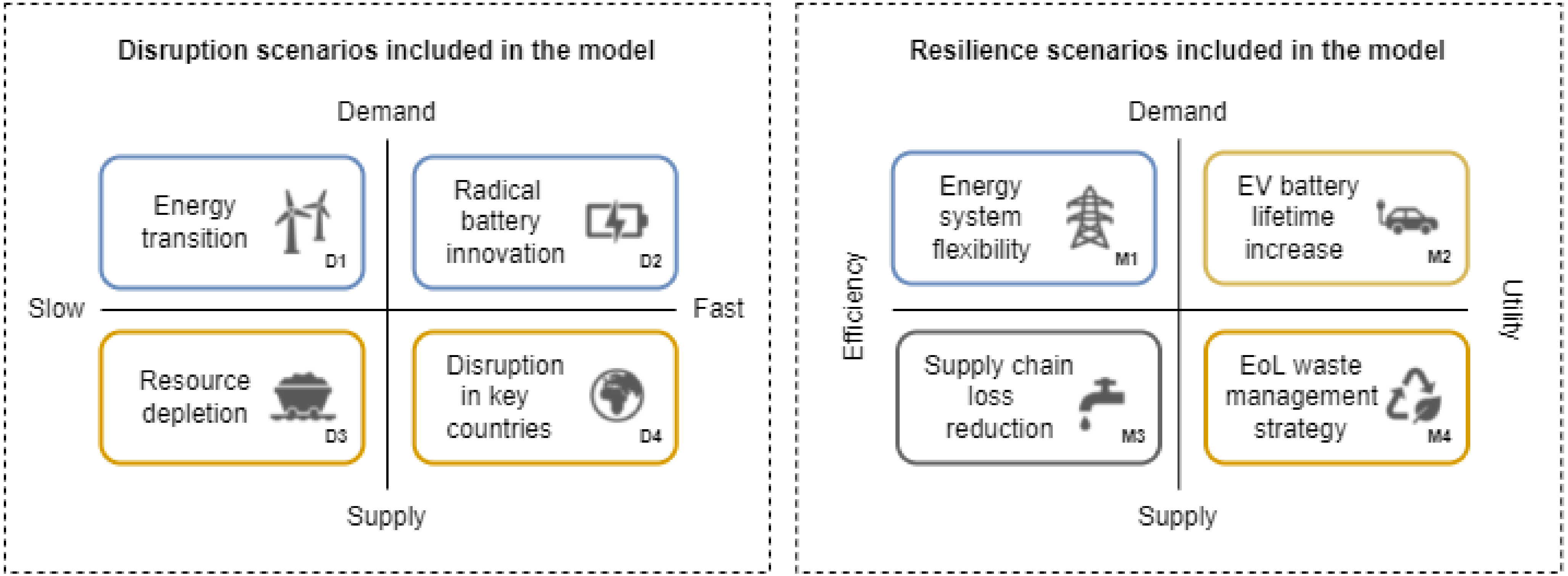
- Resources, reserves and ore grades per mine (652 projects)
- Data on ore type, by-product composition, processing method, etc.
- Aggregated global consumption and secondary supply per sector
- Mechanisms for exploration, capacity increase and mothballing

Nickel model structure

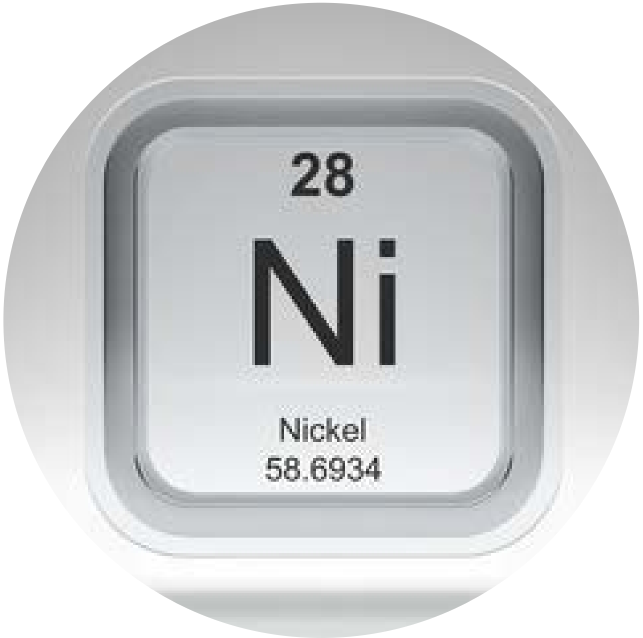
Price	Impacts
Costs include: energy, royalties, reagents & other, carbon price, fixed costs, capital costs	Dynamic, regional resource depletion
Option to include or exclude by-products (3 mining energy allocation methods)	Dynamic, regional by-product production (mainly cobalt and palladium)
Price is based on the marginal costs allocated to nickel and scarcity	Dynamic, regional final energy use
Profit based on the marginal costs of the deposit, nickel price and by-product prices	Dynamic, regional greenhouse gas emissions


Capacity allocation pulse
<Mothballed>
Sum added capacity
Upper bound maximum profit deficit
Lower bound maximum profit deficit
Average minimum profit surplus as percentage of investment
Minimum profit surplus
Mothballing
Initial C&M
<Nickel ore grade>
<Paradigm switch>
Maximum mothball time
Into C&M
Mothball time
Out of C&M
<Mothballed>
<Primary nickel scrap>
Nickel out
Nickel in
Nickel supply
Changes in stock
<Recycling>
<Consumption>
<Cumulative final demand>
<TIME STEP>
Global maximum capacity increase percentage
Capacity increase
New brownfield capacity
<Invested capital costs>
Upgrade time
Lower bound minimum profit surplus
Lower bound minimum profit surplus as a percentage of investment
Mothballed
Decomissioning
<Current potential profit>
Pos profit
Profit surplus
Neg profit
<TIME STEP>
Nickel consumption
Cumulative consumption
Difference cumulative demand and consumption
<Total existing capacity>
<Average concentration nickel in Earth's crust>
<Unit manipulation nickel ore grade>
Upgrade intention
Upgrade delay
<Profit surplus>
Restarting
Parking
<Cumulative mined nickel>
<Initial total resources>
Negative profit
Profit deficit
Positive profit
<Sum upgrading>
Global maximum capacity increase
Minimum capacity
<Nickel reserves>
Maximum capacity
Sum upgrading
Additional capacity
Ramping up
<TIME STEP>
<Profit deficit>
<Maximum profit deficit>
Sum mothballed
<Mothballed>
<Current profit>
Total existing capacity
Total existing and developing capacity
<Sum developing>
<Capacity allocation pulse>
Consumption forecast
<Demand request>
Capacity increase allocation
<Existing capacity>
Potential added capacity
Upgrading existing mine
Sum operating
Operating capacity
Initial operating
Existing capacity
<Initial status>
Total existing mining capacity utilisation
Total capacity a year ago
Global capacity change
Global capacity increase percentage
Consumption forecast short period
<Short forecasting period>
<TIME STEP>
Sum developing
Width
Average mine operation plan
<Project ore type>
Developing new mine
New mine
Starting up
<Project country>
Initial average mine production per country
<Minimum capacity>
Initial average capacity utilisation
Sum mining
Global capacity increase
<One year>
<Number of projects>
<Nickel ore grade>
Average mine operation plan for existing mines
<TIME STEP>
<INITIAL TIME>
Total operating mining capacity utilisation
<Mining resources>
<Project country>
<Percentage class 1>
<Percentage of primary scrap>
Initial developing
New mine intention
Development time
Development delay
Share of operating capacity per country
Largest share of operating capacity
Class distinction
Share of processing per country
<Primary nickel scrap>
<Consumption>
Consumption forecast
<Percentage lost during production>
<Forward supply chain loss reduction switch>
<Delay order consumption forecast>
<Final investment attractiveness ranking>
<Potential added capacity>
New greenfield capacity
<Initial status>
Lower bound development time
Upper bound development time
<Project investment attractiveness>
Sum reserves
Total operating capacity
Country to shut down
<Project ore type>
<Project class>
<Smelting and refining>
<Production losses>
Required refined nickel
<Capacity allocation pulse>
<Minimum capacity>
<Project country>
<Country to shut down>
<Sum mining>
Sum mining reserves
<Nickel reserves>
Mining capacity utilisation
<Mining>
Total mining per ore type
Processing and recycling
Finished nickel stock per class
Use and losses
<Class based demand>
Additional processing required
Consumption forecast long period
<Final nickel demand>
<Long forecasting period>
Potential projects with insufficient initial resources
Exploration
<Paradigm switch>
Power for price based exploration
<Relative increase exploration given expectations of the energy transition>
Option to mine resources switch
Projects to shut down
Sum mining resources
Supply chain
R over P ratio
Initial nickel stock
<Recycling>
<Initial class fraction>
Percentage class 1
Minimum stock transit time
Delayed percentage class 1
<Delayed battery fraction of class 1>
EoL CR improvement
<Time>
Mining resources
Supply disruption switch
Initial mined stock
Initial percentage mine stock
Initial finished stock
Final nickel availability
Initial consumption per class
<Demand request>
Change in EoL CR
EoL CR
<EoL management of batteries switch>
Sum initial total resources
Initial resource base nickel
<One year>
Administration time
Sum discovery
Sum measured and indicated
<Percentage lost during mining>
<One year>
<Operating capacity>
<Projects to shut down>
<Initial number of operating mines>
<Initial status>
Consumption
Initial resources lower than minimum required
Undiscovered nickel deposits
Initial exploration
Inferred nickel resources
Further discovery
Measured & indicated resources
Economically mineable
Nickel reserves
Mined nickel stock
Mining
Smelting and refining
Finished nickel stock
Nickel in use stocks
Initial use stocks
Initial EoL collection rate
Resource mining losses
<Initial status>
<Time>
<One year>
Sum mined
Sum processing
Percentage lost during production
<Average lifetime class 2>
Secondary nickel scrap
<Average lifetime storage technologies>
Percentage of total mined nickel in use
<Minimum capacity>
Initial total resources
Sum exploration
Sum inferred
Initial resources
<Forward supply chain loss reduction switch>
Initial reserves
Economically mineable tailings
Mining losses
Processing losses
<Project process>
Production losses
<Percentage class 1>
Percentage of primary scrap
Use losses
<Forward supply chain loss reduction switch>
Delayed class fraction
Initial percentage of use in scrap
Initial total nickel in the economy
<Average mine operation plan>
Total resources
<Measured & indicated resources>
Combined resources
Tonne per megatonne
<Economical>
<Existing capacity>
<Resource mining losses>
Percentage lost during mining
Share of processing per technology
Intensity of stockpiling
Resources lower than minimum required
<Nickel reserves>
Sum total resources
<Average mine operation plan for existing mines>
<Existance of mines>
<Current potential profit>
Existing classes
<Forward supply chain loss reduction switch>
Percentage lost during processing
Stockpiling inclusion switch
<Current profit>
Delay order primary scrap recycling
Primary nickel scrap
Delayed class based demand
<Fraction of batteries with shorter lifetime>
<Nickel mined before 2015>
Potential projects with insufficient resources
Resources to reserves
<Resource class presence>
<Further discovery>
<Annual opportunity identification>
Economical for existing capacity
Existance of classes
Mining losses resources
<One year>
Current potential mining
Average time mining to refining
Initial recycling input rate
Potential recycling input rate
Primary scrap to be recycled
<Class based demand>
Average lifetime class 1
<Battery replacement delay time>
Initial EoL recycling rate nickel
<Future potential profitability of classes>
Average time scrap to recycling
<Percentage class 1>
Exploration
Inferred in classes
Discovery
Measured & indicated in classes
<One year>
<TIME STEP>
Economical
Reserves in classes
Economical tailings
Mine tailings
<Initial resources>
<Existing capacity>
Recycling input rate
Recycling
Nickel scrap
Initial scrap stock
Initial EoL recycling rate stainless steel
Mined or lost resources
<Resource class presence>
<Initial status>
<One year>
<Smelting and refining>
<Delayed class fraction>
Initial class fraction
<Initial exploration>
Resource class division
Resource class presence
Fraction per class mined resources
<Mining resources>
<Current profit>
Mined or lost
<Tonne per megatonne>
Tailings losses
Forward supply chain loss reduction switch
<Average lifetime class 1>
<Average lifetime class 2>
Sum recycling
Difference nickel content scrap and ore grade
EoL PR
Scrap losses
Total EoL RR
Initial EoL recycling rate class 1
<Tonne per megatonne>
<Initial status>
Initial measured & indicated resources
<Future potential profitability of classes>
<Current potential profit>
Fraction per class mined
Percentage lost in tailings
<Final nickel demand>
Nickel content scrap
EoL management of batteries switch
<Overall average nickel ore grade of existing mines>
EoL RR
<EoL CR>
Initial EoL processing rate class 1
<Initial resources>
<Measured & indicated resources>
<Resource mining losses>
Opportunity identification
<Mining losses>
<Mining>
<Nickel reserves>
<Opportunity identification>
Delayed nickel demand
Delayed battery fraction of class 1
Initial nickel content scrap considering batteries
<Unit manipulation nickel ore grade>
Initial nickel content scrap
Maximum nickel recycling efficiency
Initial difference nickel content scrap and ore grade

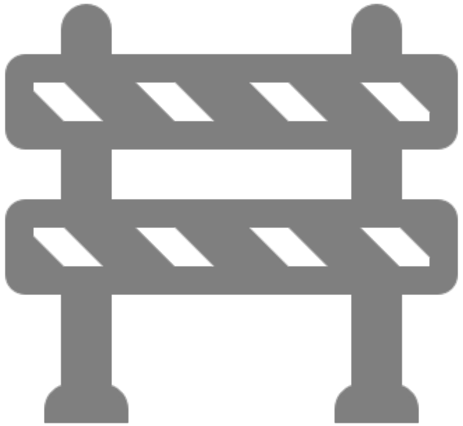
Disruption & resilience scenarios



Nickel Results



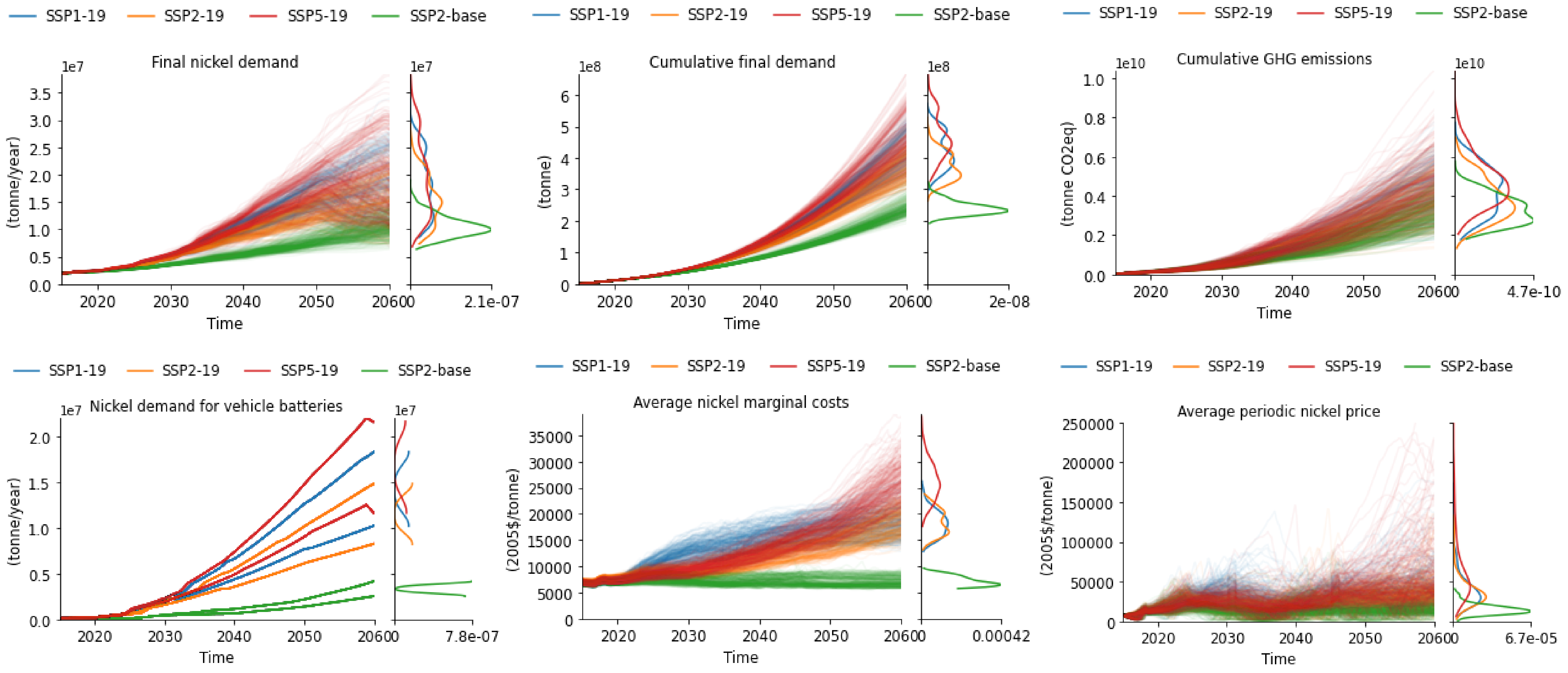
Nickel results



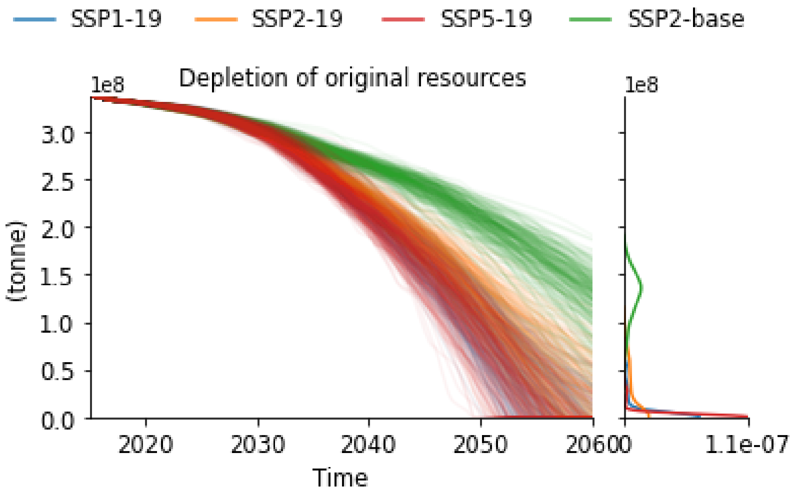
Disruption scenarios

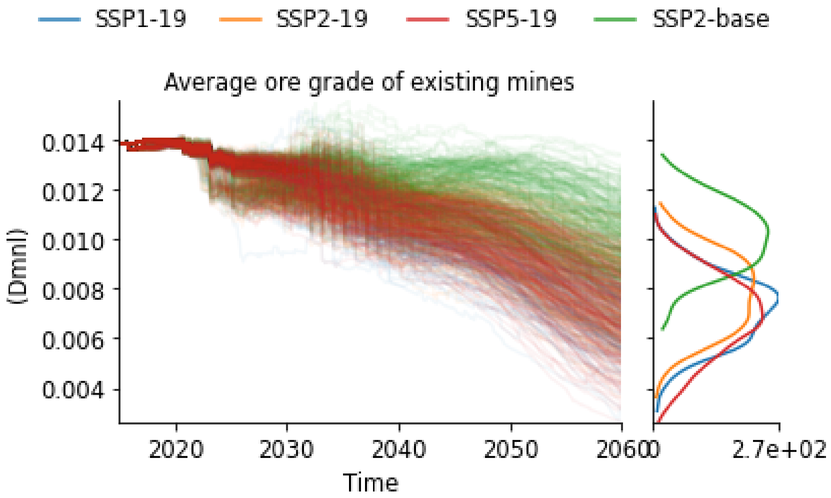
Resilience scenarios

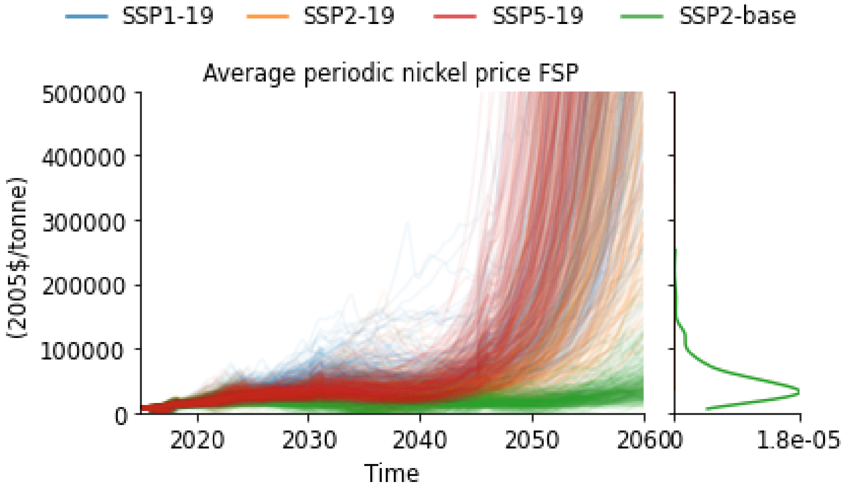
Energy transition

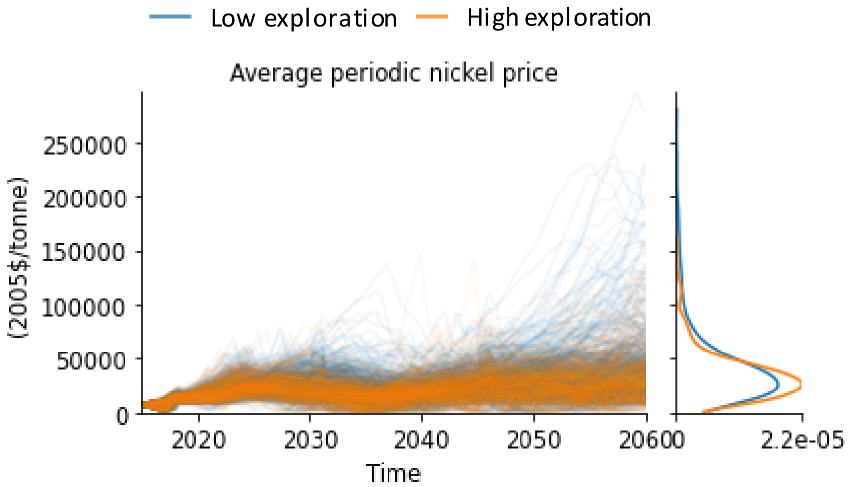


Resource depletion



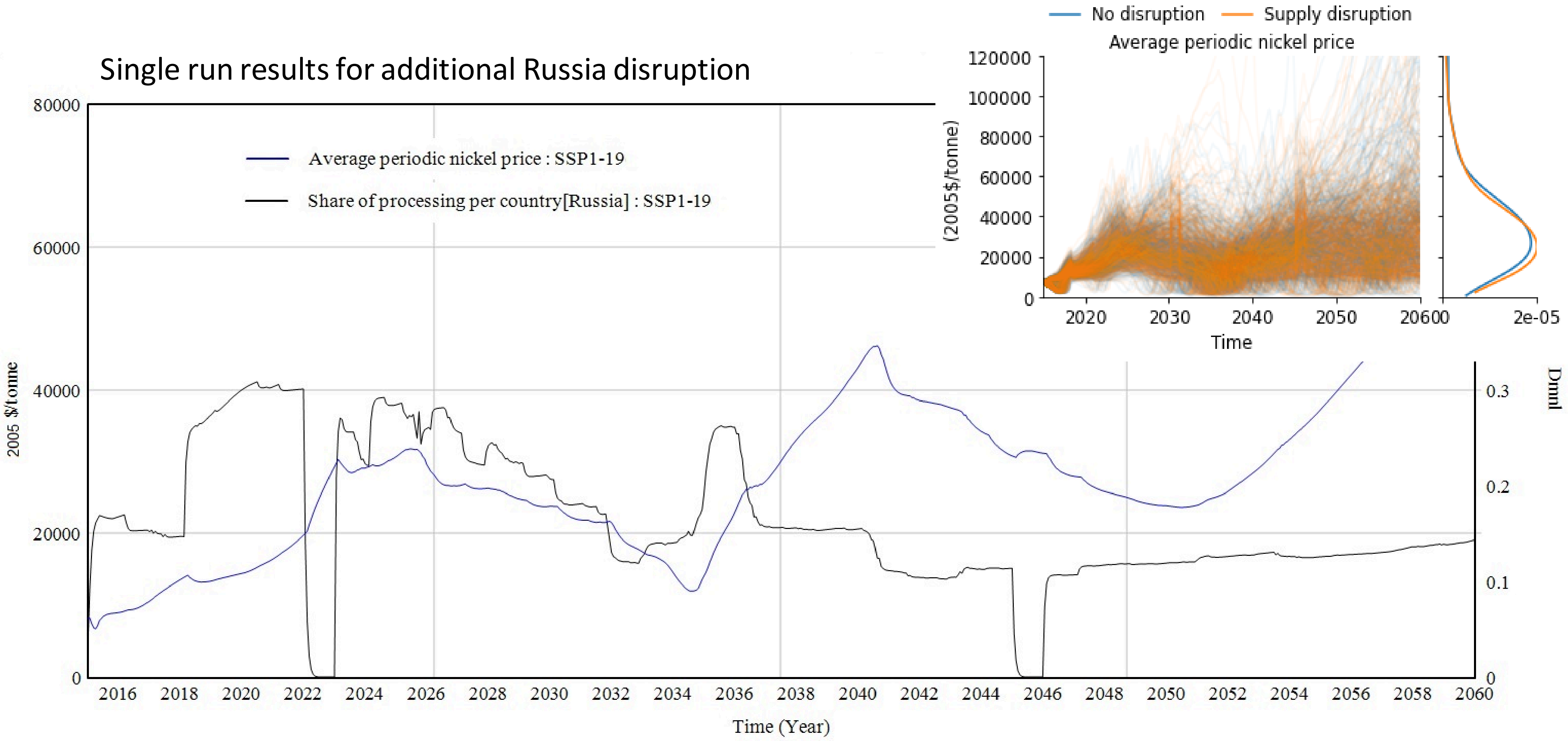






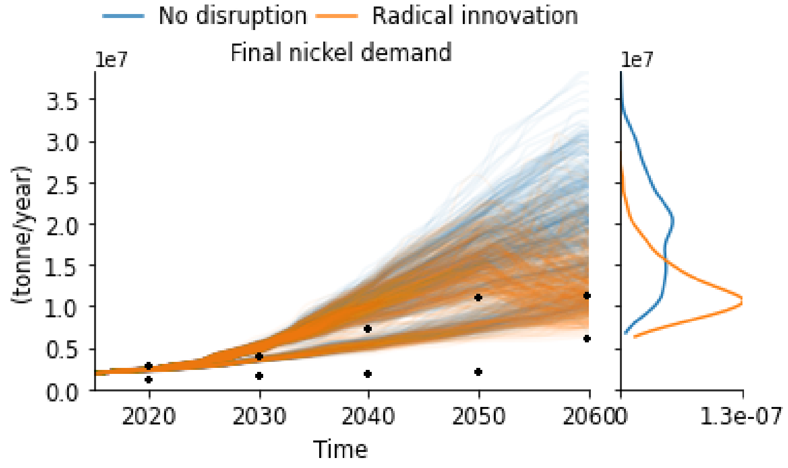
Supply disruption

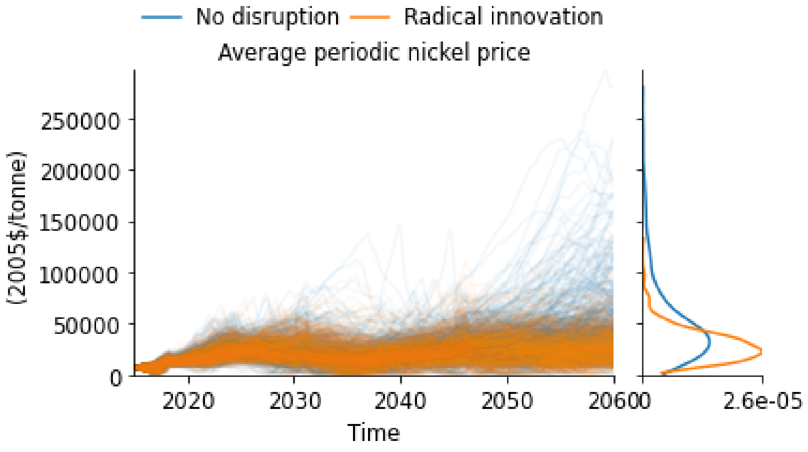
Single run results for additional Russia disruption



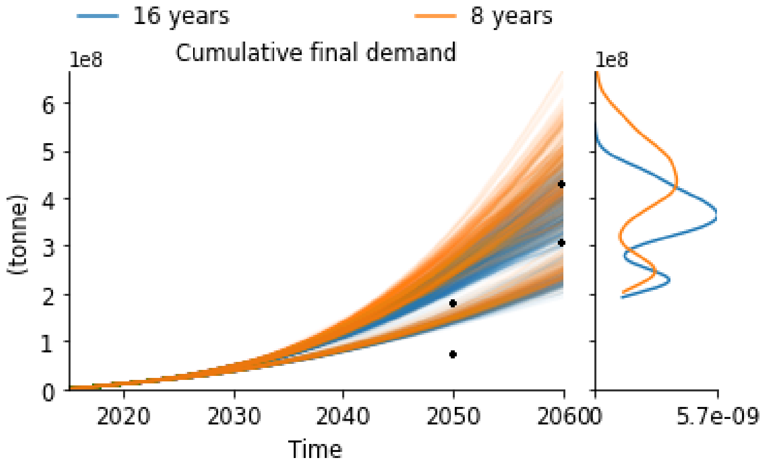
Resilience scenarios

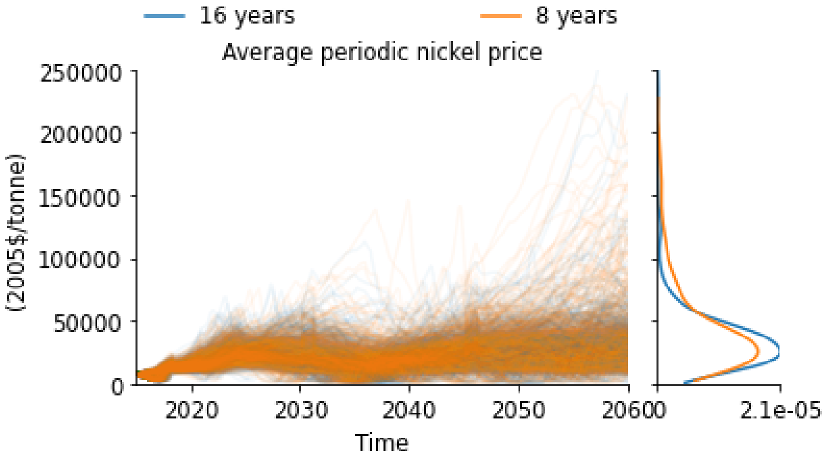
Radical Innovation*



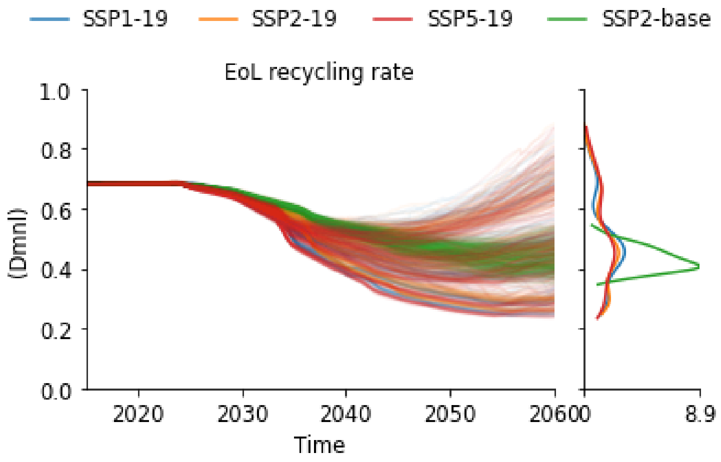


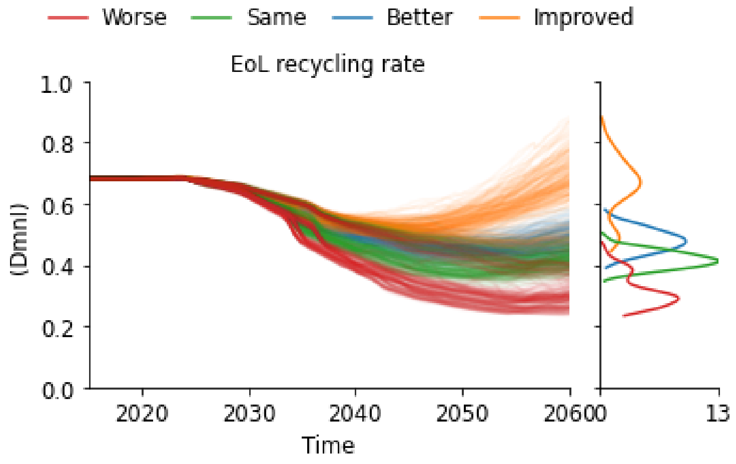
Battery lifetime increase





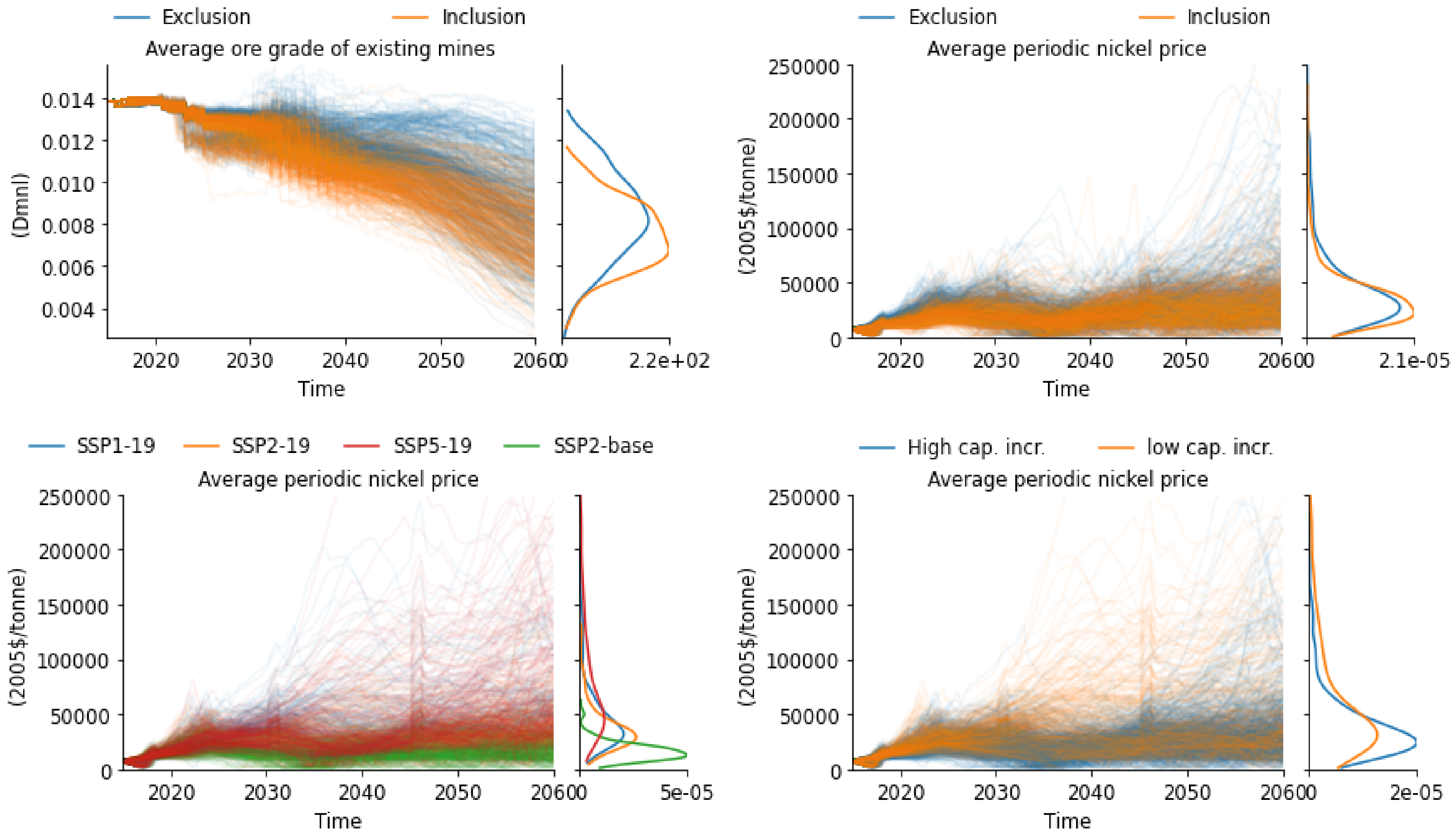
EoL waste management





Other scenarios and uncertainties

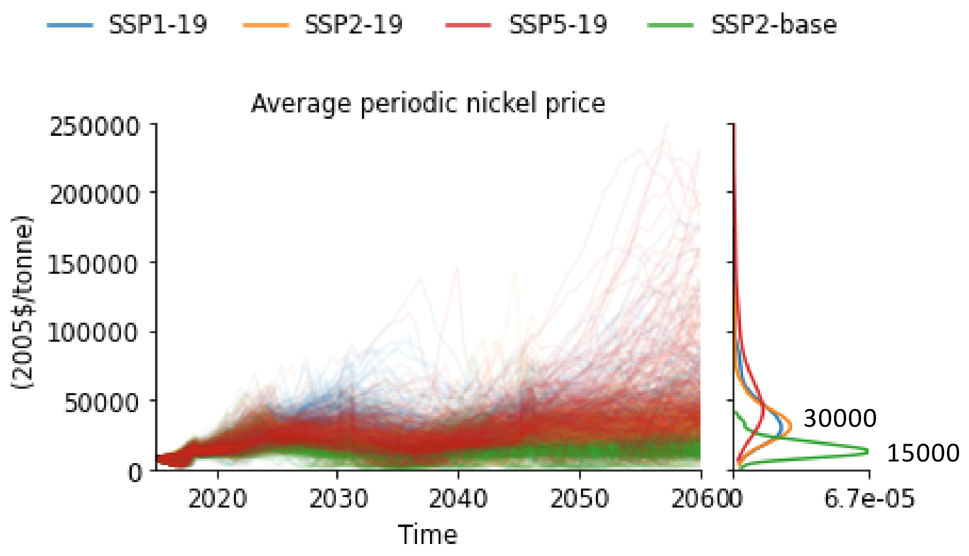
- Resilience scenarios that did not have much impact:
  - Energy system flexibility
  - Supply chain loss reduction
- Other uncertainties with a large impact
  - By-product inclusion
  - Maximum rate of capacity increase



Conclusion

The nickel system is:

- Resilient to partial substitution and to a one-year supply disruption compromising the top supplying country.
- Conditionally resilient to ore depletion and the energy transition



Factors contributing to resilience: