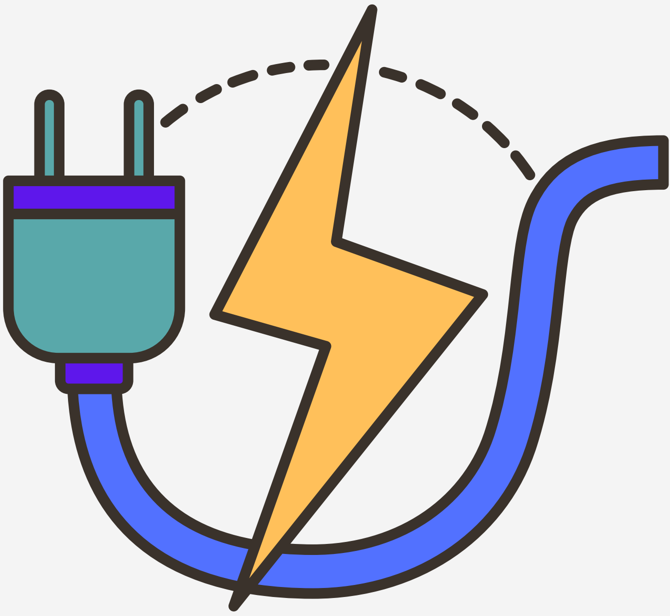

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MSC INDUSTRIAL ECOLOGY

Cobalt for the Energy Transition

Resilience of Supply Chain and Vulnerable Networks

Written By:

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Cobalt for the Energy Transition:

Resilience of Supply Chain and Vulnerable Networks

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In Partial Fulfilment of the requirements for the degree of
Master of Science
In Industrial Ecology
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Under the supervision of:
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Abstract

Cobalt is an essential component in the energy transition. If you are currently reading this abstract on a tablet, smart phone, or laptop the end-use of cobalt is right in front of you. Consumption of cobalt is expected to increase about 40% between 2021 and 2015, demand mainly being attributed to Electric Vehicles and Batteries. Therefore, for a successful transition to renewable energies and zero-emission mobility it is important to have a resilient supply chain of cobalt products. This research contributes to the knowledge of cobalt research by analyzing weighted bilateral trade data using an ecological perspective for cobalt products needed for the energy transition, considering products involved in the upstream and downstream of the supply chain. Previous research has mainly focused on products at the supply stage, and this paper is the first to use Ecological Network Analysis to analyze resilience of cobalt at all supply chain stages over the past nine-years. Ecological Network Analysis was used as it considers that network structures have implications for the resilience of a network, and the dual perspectives of redundancy and efficiency are measured to analyze resilience. The results of this research have shown that most cobalt products for the energy transition have redundant networks, making them less susceptible to supply chain shocks; it has identified products of concern using the results from the ENA; and it identifies the major importers/exporters/bridge nodes for the products of concern and considers how strong their governance is, as governance can affect trade. One important product of concern are metals in the form of wire that are used in solar energy, this trade network is extremely vulnerable to supply chain shocks. This can cause issues as there is solar expansion taking place at a large scale. This study also found products of concern at the process stage (refined cobalt) and the manufacturing stage (for biomass energy). This study aims to give a more complete picture as to what resilience has looked like and what can potentially happen if networks follow their historical trend.

Keywords

Cobalt, Supply Chain Analysis, Metal Criticality, Network Analysis, Ecological Network Analysis, Resilience, Energy Transition, Renewable Energy, Mobility Transition

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Acronyms

CRM	*Critical Raw Materials*
DRC	*Democratic Republic of Congo*
ENA	*Ecological Network Analysis*
EU	*European Union*

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1 Introduction

1.1 Problem Statement

Resilience is an important concept, especially when linked to a sustainable future. This has been recognized by the United Nations as resilience is explicitly linked in some Sustainable Development Goals (SDG), while other SDG's have targets and indicators that capture dimensions of resilience (ESCAP-ADB-UNDP Asia-Pacific SDG Partnership, 2018). This is also increasingly important for the 2° IPCC scenario, where renewable energy would need to provide as much as half the world's energy needs by 2050 (Krewitt, et al., 2007). To allow for better management of energy supply and demand countries have banded together to begin transitioning to a sustainable energy system, as seen in treaties such as the Kyoto Protocol (1997) and Paris Agreement (2015) (Solomon & Krishnab, 2011). Renewable energy and energy efficiency measures can potentially achieve 90% of the required carbon reductions, with two-thirds of emissions reductions (20Gt per year in 2050) being attributed to renewables (International Renewable Energy Agency, 2017; Solomon & Krishnab, 2011).

As renewable energies are on the rise in the global north, the demand of the intermediary products for these renewable energies has increased along with the demand of the primary and refined materials necessary for this transition. For the energy transition needed to reach the 1.5-2° scenario, consumption of metals which are components of the materials for renewables would increase, some metals needed for the sustainable transition are CRM (Arrobas et al., 2017). CRM are materials which have been selected by European Commission and deemed as critical for society and the economy, additionally these materials have a high-risk associated with their supply and have a lack of viable substitutes (CRM Alliance, n.d.). One of these CRM is cobalt, which is used in renewable energies, electric vehicles, and energy storage – which should rapidly increase in production under the 1.5-2° scenario (Arrobas et al., 2017). Cobalt is considered a CRM due to its high economic importance and lack of primary cobalt production within Europe, leading to high dependence on imports, where access is uncertain due to geopolitical elements of its suppliers.

In 2020, 55% of Cobalt was used for batteries of electric vehicles, which has contributed the growth spurt in production of 38,000 tonnes/year globally from 1970- 2009 to 145,000 tonnes/year globally from 2010-2019 (The Faraday Institution, 2020). Most of the world supply of cobalt is found in the DRC; it is the largest exporter, making up to 88% of global exports (van den Brink et al., 2020). Almost all cobalt, apart from production in Morocco and artisanal mined cobalt in the DRC, is mined as a by-product of copper and nickel. Alternatively, there are also efforts in recycling of cobalt that provide some circularity within the supply chain, in the EU as of 2020 the end-of-life input recycling rate is 35% (Bobba, et al., 2018). However, the growing demand for cobalt and the limited stock in Europe does not allow for secondary cobalt material to have a significant market share. This ensures that there will continue to be dependence on cobalt products made from primary material imports until stocks are large enough and technology is developed enough to provide a viable circular and domestic alternative. Therefore, for a successful transition to renewable energies and zero-emission mobility it is important to have a resilient supply chain of cobalt products.

To date, supply chain management has focused on lean supply chain planning using six-sigma methodologies and just in time planning. These strategies focus on moving product just as it is needed in the manufacturing process to keep a lean manufacturing style and reduce the need for storage. This manufacturing style is popular as it reduces waste associated with overproducing and holding inventory; therefore, increasing cash flow, and reducing overhead. However, there are issues associated with it, such as dependence on reliability and consistency of all links in the supply chain (Cheng & Podolsky, 1996). As there are no safety stocks or excess capacity there is no buffer if the supply chain becomes unreliable (Cheng & Podolsky, 1996). Interruptions in supply chains can be caused by pandemics, trade wars, globalization, and climate change (Handfield et al., 2020; Roscoe et al., 2020). They also have huge effects on industries and our daily lives, as seen recently with the war in Ukraine and interruptions to the supply of gas from Russia. These interruptions in the supply chain cause consequences to the individual, the economy, and the value of currency. If these networks are not resilient and there is a major shock to the system, the just in time strategy does not account for these potential disturbances. Due to this, there should be more importance on understanding the balance between efficiency and redundancy in global trade networks, as the supply chain management tend to focus on efficiency. To prevent cessations of different supply chains, there should be an assessment of their resilience in an objective and empirical way.

1.2 Ecological Network Analysis for Resilience

Khazzari et al. (2017) reported that most of the research on international trade networks has focused on binary relationships, or un-weighted flow links. ENA is a methodology that can be used to analyze the complexity of weighted bilateral trade networks, and it can help understand the resilience of the globalized network of cobalt products. The ENA methodology analyzes systems interactions to identify holistic properties that are not able to be directly observed (Fath et al., 2007). It was initially created to analyze the resilience of food webs and emphasize the importance of the ratio between the system redundancy and efficiency for resiliency in the system (Kharrazi et al., 2017; Ulanowicz, 1991). ENA considers that network structures have implications for the resilience of a network, and the dual perspectives of redundancy and efficiency are measured to analyze resilience using this methodology. Understanding the efficiency or redundancy of the system allows understanding of how vulnerable it is to supply chain shocks, and it can show which global trade networks need more attention to build resilience or diversity of trade.

1.3 Research Gap

Currently the literature on the cobalt supply chains has focused mainly on the resilience of cobalt supply. Earl et al. (2022) did a review on the future evolution of the supply of cobalt, considering primary and secondary sources, through technologically resilient and environmentally sustainable pathways. The other literature discusses various critical metals needed for final products (lithium-ion batteries), assessments of supply chain issues for technologies in the energy transition, or detailed analysis of other CRM (Yan et al., 2020; Blagoeva et al., 2016). van den Brink et al. (2020) has the most extensive analysis on the resilience of the cobalt supply chain. Their research identified resilience by exploring and visualizing the global supply chain using an electrical network analysis; it considers the countries, mines, mine operators, mine shareholders, and refineries, evaluating risks of the post-mining stage. This research noted that the previous literature on cobalt has focused mainly on the supply stage, neglecting post-mining stages. van den Brink et al. (2020) were the first to consider post-mined cobalt into research on resilience. According to Chapman et al. (2013) is important to look at post-mining as assessing the supply risk at different stages in the value chain can render different results.

1.4 Research Objective

This research provides an evaluation of the weighted and directional trade network for cobalt products needed for the energy transition, considering products involved in the upstream and downstream of the supply chain. This research is novel as it is the first to use ENA to analyze CRM networks. This research measures the resilience of cobalt including manufactured products, this research is the first to investigate the resilience of various products which are primary, refined, and intermediate/final products; therefore, looking at all stages of the cobalt supply chain. This research is focused solely on cobalt products needed for the energy transition and evaluating these important factors to understand the state of their supply chains. The purpose of this thesis is to understand whether existing trade networks show vulnerability that jeopardizes the energy transition and aims to identify points of concern. This research is directed to individuals involved in the energy and transportation, industry, relevant government officials (mining and industry departments), cobalt stakeholders (at all points in the supply chain), and researchers.

This research is conducted as part of the Industrial Ecology master's program and uses many of its guiding principles. This thesis considers the issue of the energy transition, which is necessary to achieve a reduction in carbon emissions and achieve net-zero climate goals. The supply chain of the products for the energy transition is affected by issues on the human level, such as wars and pandemics which affect the ability of humans to provide labor affecting the supply chain. This thesis uses an interdisciplinary approach by including governance in the methods of evaluation. The energy transition is considered a complex systems problem and this thesis aims to do that justice.

1.5 Research Questions

The main research question being answered is:

Is the global supply chain of cobalt jeopardizing the energy transition?

To answer the overarching research question, several subsequential sub-research questions were created. The questions were created to break down the main research question into coherent steps that would lead to understanding the supply chain in the recent years and how its trends can indicate potential areas of concern for the energy transition.

SQ1: What has the resilience of cobalt products been over the past nine years?

SQ2: Which cobalt products are the most vulnerable to supply chain disruptions?

The resilience of the products is evaluated using an ENA and provides insights into the resilience of products at different levels of the cobalt value chain, including primary material, and the post-mining stages of refined, intermediate, and final products. Once the resilience has been calculated over the years an average value will be collected to understand the resilience over the years and its trend. This will be used to understand which products are vulnerable to supply chain shocks. These products are labeled 'products of concern' as their networks are already vulnerable or are of concern as their networks are becoming more vulnerable.

SQ3: What is the trade network of products of concern?

The networks for products of concern are explored by visualizing their global trade networks. The important nodes in the network are explained using centrality analysis combined with governance indicators to show the potential vulnerabilities in trade that stem from issues in governance.

The diagram below visualizes which research methods answer the research questions. With the overarching research question being answered by all three sub-research questions.

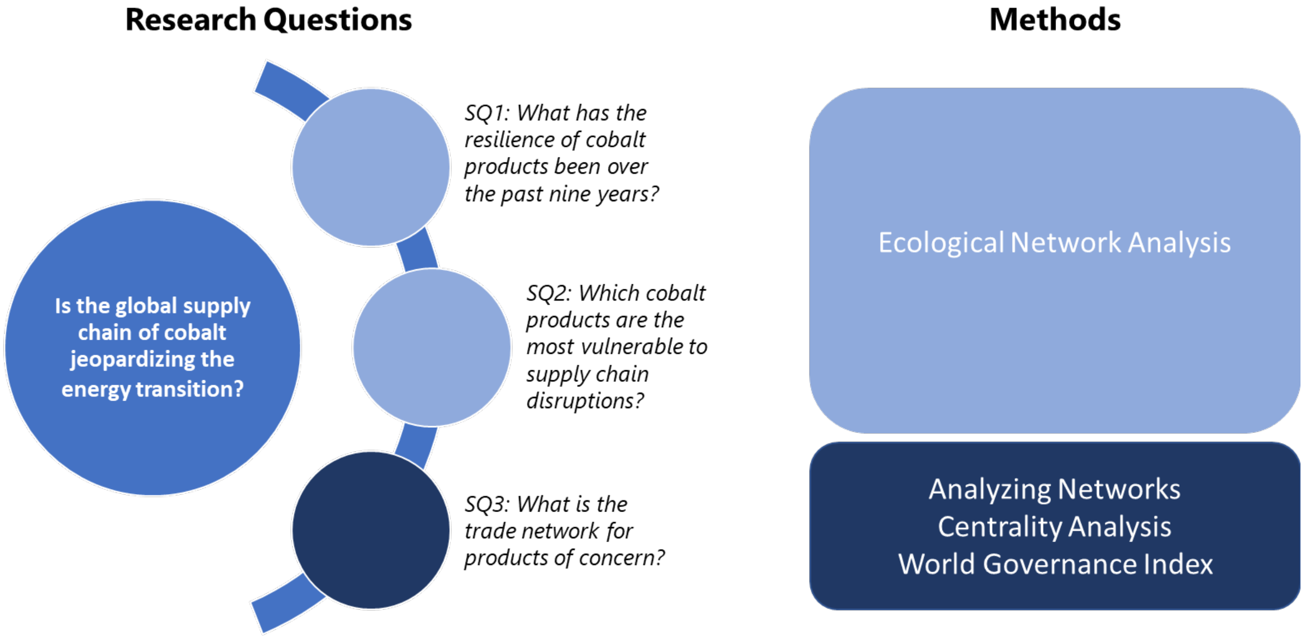


Figure 1: Research Diagram

2 Materials

This section will review the process of selection for cobalt products, the sources used, and the database used for the ENA and network analysis.

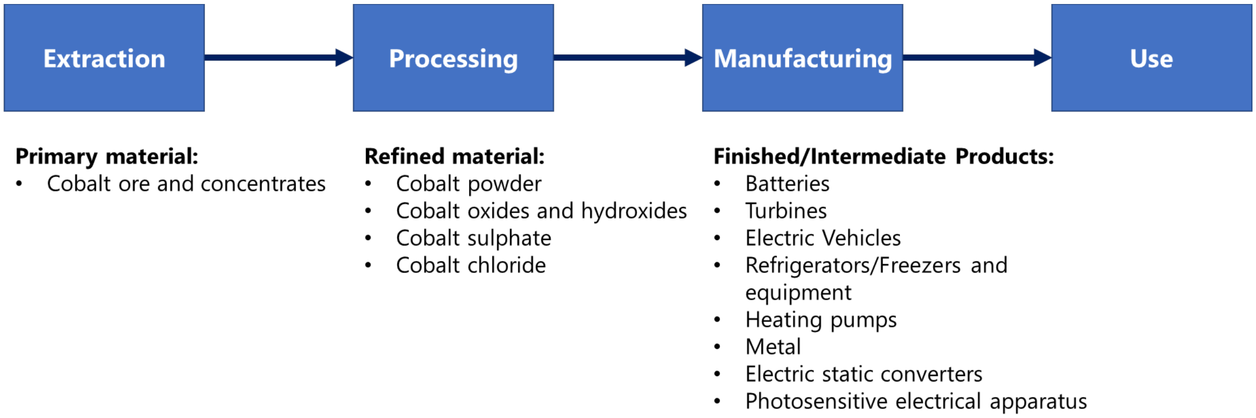
2.1 Selection of Products

To identify the cobalt products needed for the energy transition, the levels of the supply chain should be considered. The products were divided into the supply chain stages of extraction (primary material), processing (refined material), and manufacturing (intermediate/finished product).

The primary and refined cobalt products, which belong to the extraction and processing stage of the supply chain, were identified using the European Commission's report *Material System Analysis of five battery related Primary materials: Cobalt, Lithium, Manganese, Natural Graphite, Nickel* (Matos, et al., 2020). This report identified all the cobalt forms used in the EU economy, this report provided five primary/refined cobalt products.

The products in the manufacturing stage are intermediate and finished products. The International Centre for Trade and Sustainable Development (ICTSD) published a report which identified the four-digit HS categories relevant to main components of climate mitigation goods (Wind, 2008). This list of climate mitigation goods presented overlaps with the World Trade Organizations (WTO) 153-list. This 153-list refers to the list of commodities that was specified in the Annex to WTO document JOB(07)/54 of 27 April 2007. This WTO documents Annex concerns the description of commodities as a basis for negotiations within the context of environmental protection. The list of 85 four-digit HS categories created by the ICTSD was cross referenced with a master list of cobalt products, from the PANORAMA project, to determine which climate mitigation categories contained cobalt (Habib, et al., 2019). From this there resulted a total of 20 products; 7 which pertained to biomass, 10 to geothermal energy, and 3 to solar energy. From these twenty products 6 were removed due to lack of relevance to the renewable energy source, as the four-digit categories provided the products umbrella however all of the products under the umbrella were not necessarily directed for renewable energy. In addition to these renewable energy products, batteries and electric vehicles were considered as they are important cobalt products relevant to the energy transition, totaling 17 finished/intermediate products.

The image below, Figure 2, shows the value chain of the product with product abbreviations under the stage where is falls.



Primary material:
- Cobalt ore and concentrates

Refined material:
- Cobalt powder
- Cobalt oxides and hydroxides
- Cobalt sulphate
- Cobalt chloride

Finished/Intermediate Products:
- Batteries
- Turbines
- Electric Vehicles
- Refrigerators/Freezers and equipment
- Heating pumps
- Metal
- Electric static converters
- Photosensitive electrical apparatus

Figure 2: Mapping products along the Value Chain of Cobalt

Below is a table, Table 1, of all the identified products used in the analysis.

Table 1: Cobalt products relevant for the energy transition, these products will be used for analysis. Products were identified using the EU's report 'Material System Analysis of five battery related Primary materials: Cobalt, Lithium, Manganese, Natural Graphite, Nickel' (Matos, et al., 2020) and the International Centre for Trade and Sustainable Development's report 'HS Codes and the Renewable Energy Sector' (Wind, 2008).

HS6	**Product Name**	**Category**
260500	Cobalt ores and concentrates	Primary and Refined Cobalt
282200	Cobalt oxides and hydroxides; commercial cobalt oxides	Primary and Refined Cobalt
282739	Cobalt chlorides	Primary and Refined Cobalt
283329	Sulphates of cobalt and of titanium	Primary and Refined Cobalt
810520	Cobalt mattes and other intermediate products of cobalt metallurgy; unwrought cobalt; cobalt powders	Primary and Refined Cobalt
840681	Turbines: steam and other vapour turbines, (for other than marine propulsion), of an output exceeding 40MW	Biomass
840682	Turbines: steam and other vapour turbines, (for other than marine propulsion), of an output not exceeding 40MW	Biomass
841199	Turbines: parts of gas turbines (excluding turbo-jets and turbo-propellers)	Biomass
841810	Refrigerators and freezers: combined refrigerator-freezers, fitted with separate external doors, electric or other	Geothermal Energy
841830	Freezers: of the chest type, not exceeding 800l capacity	Geothermal Energy
841840	Freezers: of the upright type, not exceeding 900l capacity	Geothermal Energy

841850	Furniture incorporating refrigerating or freezing equipment: for storage and display	Geothermal Energy
841861	Heat pumps: other than air conditioning machines	Geothermal Energy
841869	Refrigerating or freezing equipment	Geothermal Energy
841891	Refrigerating or freezing equipment: parts, furniture designed to receive refrigerating or freezing equipment	Geothermal Energy
841899	Refrigerating or freezing equipment: parts thereof, other than furniture	Geothermal Energy
711510	Metal: catalysts in the form of wire cloth or grill, of platinum	Solar Energy
850440	Electrical static converters	Solar Energy
854140	Electrical apparatus: photosensitive, including photovoltaic cells, whether or not assembled in modules or made up into panels, light emitting diodes	Solar Energy
870911	Vehicles: electrical, self propelled	Electric Vehicles
850650	Cells and batteries: primary, lithium	Batteries
850690	Cells and batteries: primary, parts thereof	Batteries

2.2 Database Information

For this research, the BACI database was used from CEPII which is the leading French center for research and expertise on the world economy. The BACI database provides data on bilateral trade flows for 200 countries at the product level. Products correspond to the Harmonized System (HS) nomenclature (6-digit code) (BACI , n.d.). The database includes the information from the table below.

Table 2: BACI database contents

Variable	**Description**
t	Year
k	Product category (HS 6-digit code)
i	Exporter (ISO 3-digit code)
j	Importer (ISO 3-digit code)
v	Value of trade flow (in thousands of USD)
q	Quantity (in metric tons)

BACI is created using the United Nations Statistics Division (Comtrade) data (Gaulier & Zignago, 2010). BACI reconciliates the Comtrade data, as there are sometimes repeated trade flows where imports and exports are double counted. The data is reconciliated using a harmonization system and uploaded for public access on the CEPII webpage. The BACI database is available for the different years of HS code identifications, which are updated every five years. The years available in the database are the 1992 classifications, 1996 classifications, 2002 classifications, 2007 classifications, 2012 classifications, and 2017 classifications. The 2012 classifications were used for all products, except electric vehicles, to have the most recent division of classifications while still considering nine years of trade data (2012-2020). Electric vehicles HS6 code was not present in BACI data before 2017, therefore the 2017 classification was used to analyze this product, meaning there are four years of data points (2017-2020). As of August 2022, the data in BACI is only available until 2020 on their database.

3 Methodology

This section is dedicated to explaining the methods used in this research.

3.1 Network Resilience

The trade networks are investigated through ENA, which is a framework used to identify holistic properties in ecological networks.

Resilience is the adaptive capability of the network to maintain in continuous operation when encountered with shocks and disturbances to the system (Kamalahmadi & Parast, 2016; Liang, et al., 2020). The resilience is composed of the network's efficiency and redundancy. The system efficiency reflects the constraint in flow pathways to achieve effective trade without as many connections between trade partners (Kharrazi et al., 2017). Alternatively, system redundancy reflects the diversity of network connections and pathways. The interconnectedness of a system is critical in how well the system can adapt to changes. The ability to select different agents of supply and demand is ingrained in free market principals and allows for selection and diversity of supply (Kharrazi et al., 2017). Below are the equations for efficiency and redundancy and a table explaining the meaning of the variables.

$$Efficiency = \sum_{i,j} \frac{T_{ij}}{T_{..}} log \frac{T_{ij}T_{..}}{T_{i.}T_{.j}}$$ **(equation 1)**

$$Redundancy = -\sum_{i,j} \frac{T_{ij}}{T_{..}} log \frac{T_{ij}^2}{T_{i.}T_{.j}}$$ **(equation 2)**

Table 3: Variable explanation (efficiency and redundancy), based on Kharrazi et al., (2017)

Variable	Description
T_{ij}	Flow from agent i (exporter) to agent j (importer)
$T_{i.}$	Flow leaving agent i
$T_{.j}$	Flow entering agent j
$T_{..}$	The total system throughput ($T_{..} = \sum_{ij} T_{ij}$)

The alpha metric (α) is used to reflect the tradeoff of efficiency and redundancy (Kamalahmadi & Parast, 2016; Liang, et al., 2020). It measures the order of the network, and the resilience of a network is defined based on the alpha metric (Liang, et al., 2020). The equations for the following are below.

$$\alpha = \frac{efficiency}{efficiency + redundancy}$$ **(equation 3)**

$$resilience = -\alpha \times \ln(\alpha)$$ **(equation 4)**

The optimal value for alpha is $1/e$ = 0.3679, a value higher than this optimal value indicates an overly efficient network and a value lower indicates an overly redundant network (Ulanowicz, 1991). However, as later defined by Ulanowicz et al. (2009) the flow-network sustainability is the *optimal balance of efficiency and resilience*. Therefore, to better understand which trade networks have been sustainable overtime a window of vitality is taken regarding the optimal alpha value. As seen in Figure 3, the concept of vitality is related to efficiency and resilience, which are both dependent on the interconnectedness of the network at opposite ends. The increase in efficiency reduces the resilience and vice versa, there is an unsustainable system whenever there is too much (more resilience) or too little (more efficiency) diversity in the system (Goerner et al., 2009). An overly efficient network is highly specialized but more vulnerable to disturbances within the supply chain and can break down more easily due to the lack of diversity in pathways. An overly redundant network is less specialized, however its diversity in connections allows for the network to be less vulnerable to supply chain disturbances (Liang, et al., 2020). Optimal sustainability is skewed towards resilience, meaning that it plays a greater role in optimal sustainability than efficiency does (Goerner et al., 2009). Therefore, the window of vitality taken will consider this same concept, resulting in the arbitrary range of 0.3 to 0.4.

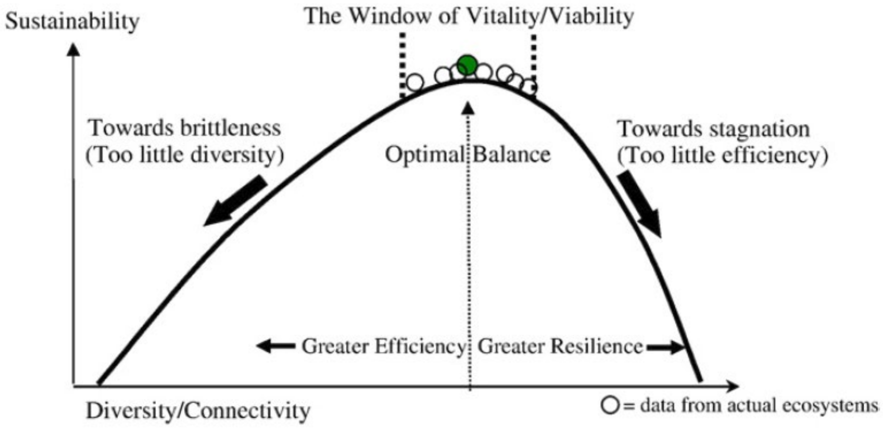


Figure 3: Window of Vitality, Source: 'Quantifying economic sustainability: Implications for free-enterprise theory, policy and practice ' (Goerner et al., 2009)

In the research the network resilience is calculated using python and its packages. Along with plotting the graphs for the network resilience throughout the years, a trendline is created to show the inclination of the data overtime. To determine the three products of concern the products which have a positive slope for the trendline, indicating that the network is becoming more efficient overtime, and have the largest average alpha values, indicating the products with the most efficient networks, are chosen. These products are selected as they are shown to have a trend where their networks are predicted to become more efficient, in a system which is or is nearing overly efficient, meaning these systems are near vulnerable and will become more vulnerable overtime.

3.2 Visualizing Networks and Centrality Analysis

The trade networks for the selected products of concern are visualized. Python was used to plot the networks along with *networkx*, *pyvis*, and *streamlit*. Networkx was used to create the network and calculate centrality measures. Pyvis created an interactive network using the information from networkx. Streamlit was used as a platform to share the networks via web-application. As there were nine years of trade data the networks are aggregated into three-year periods for efficiency of analysis. The sum of bilateral trade is taken in three-year intervals (2012-2014, 2015-2017, 2018-2020). This aggregation allows for this analysis of large amounts of trade data to be completed in a reasonable time frame and allows for a better understanding of data changes over a long time period.

International trade can become highly vulnerable due to many factors, one of them being the governance of the trading partners. Governance is important because it considers the respect of citizens and the state for the institutions that govern economic and social interactions among them (Kaufmann & Kraay, n.d.). Poor governance is a key factor in the determination of supply risks, because supply from countries exhibiting poor governance may be interrupted, e.g. through political unrest (van den Brink et al., 2020; European Commission, 2014). In order to understand how these countries in the international trade networks are performing with their governance the Worldwide Governance Indicators (WGI) project data was used, this reports aggregate and individual governance indicators for over 200 countries and territories over the period 1996–2020, for six dimensions of governance (Kaufmann & Kraay, n.d.): Voice and Accountability, Political Stability and Absence of Violence/Terrorism, Government Effectiveness, Regulatory Quality, Rule of Law, and Control of Corruption. The WGI is averaged considering all the available information for each country. The average is taken for all years as historical ranking. This is important in the context of governance, as society and world view develop slowly and are path dependent. Therefore, it is important to consider a longer period than the 2012-2020 period of trade being analyzed and investigate the 24 available years of data. This indicator value is represented by a number between -2.5 (lowest WGI ranking) and 2.5 (highest WGI ranking). The lower ranking indicates a poor score overall on the six categories and a higher ranking indicates a more favorable score overall on the six categories. These rankings are represented in the network visualizations as the color of the country, the color scale goes from red (lowest values) to green (highest values).

To better understand the networks, the weighted in-degree centrality, weighted out-degree centrality, and betweenness centrality will be analyzed.

The weighted in-degree centrality considers the number arrows going into a node considering the quantity they are carrying, calculating the total imports. This was chosen to observe the drivers of demand, the countries who are the end users of the product or use it in a value chain. This is important as their reliance on goods is what sustains the trade of product.

The weighted out-degree centrality considers the number of arrows leaving a node considering the quantity they are carrying, calculating the total exports. This was chosen to observe which are the main suppliers of products in the supply chain, these nodes are important as if they are a top supplier disruption in distribution could lead to difficultly accessing product and price changes.

The betweenness centrality quantifies the importance of the nodes based on the flow of goods by measuring how often a node is a connection on all shortest paths between two nodes. The nodes with a high betweenness centrality are most important to the flow of goods and are deemed important bridge nodes as they are important to carry goods from one node to another. This was chosen because an issue in one of these countries can majorly affect worldwide trade, rather than usual patterns the course of trade routes may need to evolve.

Below is the equation for the betweenness centrality.

$$C_B(n_i) = \sum_{j<k} \frac{g_{jk}(n_i)}{g_{jk}} \qquad \textbf{(equation 5)}$$

Table 4: Betweenness centrality variable explanation

Variable	**Description**
$g_{jk}(n_i)$	Number that node i is on
g_{jk}	The number of geodesics (shortest paths) connecting jk

The network visualization along with the supplementary information allows for a better understanding as to how vulnerable the networks for the products of concern really are. The centrality measures and information from the WGI provides context to the importance and vulnerabilities of certain countries involved in the trade network. Countries that intersected with those on the WGI and the BACI database were considered.

4 Results

In this chapter, the results of the research will be discussed. The first section reviews the results from the calculation of alpha values using ENA and identifies products of concern. The second section discusses the results from analyzing the networks, looking into the node centrality, and WGI of countries in the network.

4.1 Network Resilience

In this section, the alpha values of the products for primary and refined cobalt products, solar energy, geothermal energy, biomass, electric vehicles, and batteries will be analyzed. The results of this section determine the resilience of cobalt products and identify the products of concern, for trade networks to be analyzed in the following section. In the graph below, Figure 4, the slope of the trendline is plotted against the average alpha value of cobalt products. The table below, Table 5, provides an overview of the different products, their HS6 codes, corresponding categories, the slope of their trendlines, and the average alpha value overtime. There is a more detailed explanation of all these products with their corresponding graphs for all alpha values and their trendlines available in Appendix A: Detailed Alpha Value Analysis.

In Figure 4, the window of vitality is displayed, between 0.3 and 0.4, within this window there are seven products (HS: 810520, 850690, 840681, 282739, 841891, 840682, and 282200). Four of these products belong to the manufacturing stage and three of these products belong to the processing stage. The products in the manufacturing stage belong to intermediate/final products involved in biomass, geothermal, and batteries. The cobalt products that belong to the processing stage are all refined cobalt products.

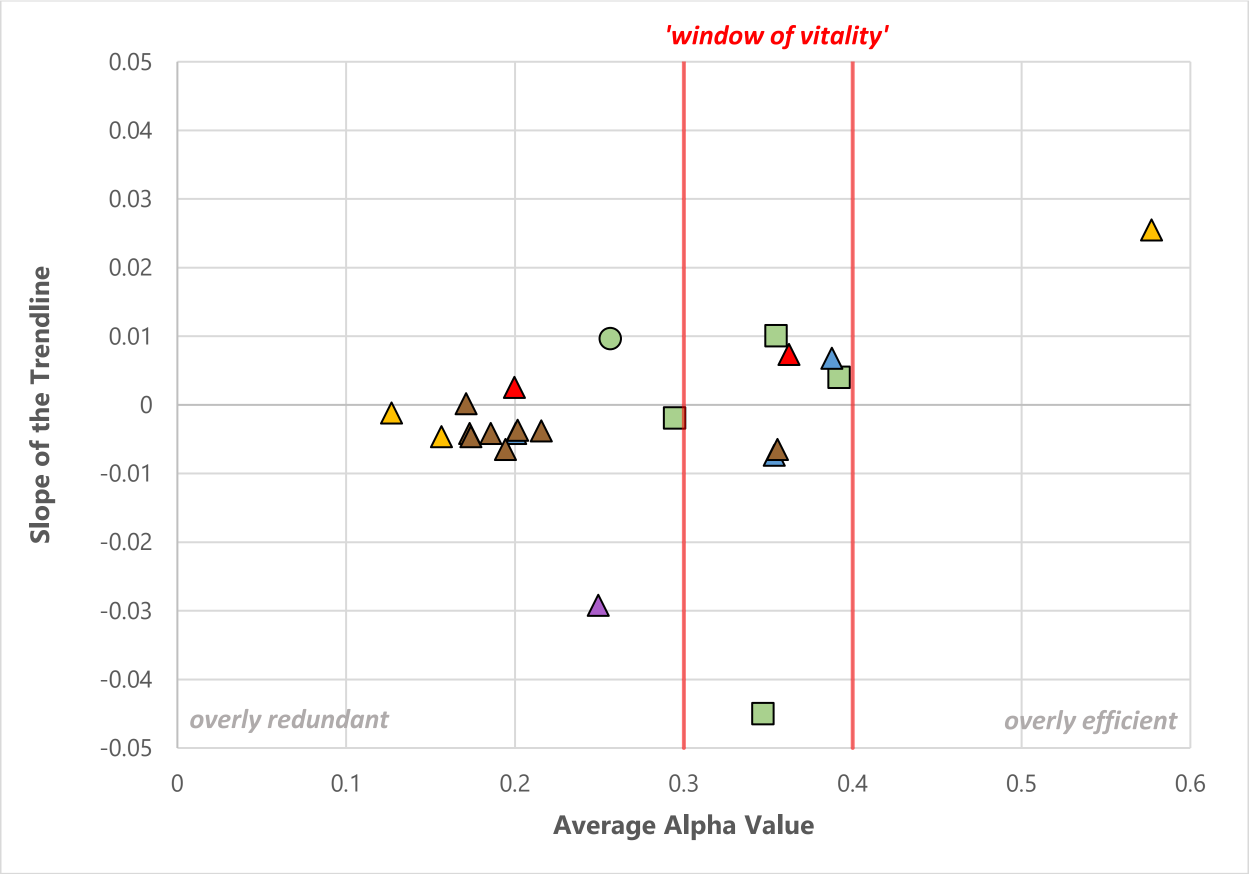
Figure 4 and Table 5 show that most of the products are clustered towards a slope value of zero, with all geothermal and biomass products having a slope ranging between 0.01 and -0.01. Most products being clustered toward the middle shows that the trend of resilience is quite consistent throughout these products. The outliers are *Metal: catalysts in the form of wire cloth or grill, of platinum* (the yellow triangle at the top right), *Electric Vehicles* (the purple triangle with a slope of -0.03, and *Cobalt oxides and hydroxides; commercial cobalt oxides* (green square at the bottom within the window of vitality).

Most products, 14 of 22, have a negative slope for their trendline, indicating that their system is become more redundant, or resilient, overtime. Three products within the window of vitality have a negative slope, the one for *Cobalt oxides and hydroxides* being the lowest of all products. There are eight products with a positive trendline (HS6: 711510, 810520, 260500, 850690, 840681, 282739, 850650, 841869) suggesting that the graphs are moving toward a more efficient system. Four of which are in the window of vitality, and all have a slope between 0 and 0.01. Three of the four products with a positive slope are primary and refined cobalt products, with *Cobalt Mattes* and *Cobalt ores and concentrates* having two of the three highest slope values. *Cobalt ores and concentrates* have a lower average alpha meaning that their network has been more resilient overtime. There is only one product with an overly efficiency system outside the window of vitality which is *Metal: catalysts in the form of wire cloth or grill, of platinum*. This product not only has the highest average alpha value, but it also has the highest slope.

Most products are overly redundant, with a large concentration of products for geothermal energy, 2/3 of solar products, electric vehicles, one of two battery products, and 1/3 products for biomass. The cluster of products that have a lower average alpha value and a slope near zero are not changing in an extreme manner, as indicated by nine-years of network data. If the trend stays consistent these products will become slightly more redundant or efficient but will remain resilient over the coming years, based on the slope trend. Electric vehicles have a more negative slope value, however, this product only has three years of data available to analyze, where one of the three years was affected by COVID-19's influence on the global supply chain. Lithium-Ion batteries which are an important driver of cobalt have an average alpha value which is overly redundant, this network has remained below the optimal alpha throughout 2012-2020. However, the trendline of the system is positive however still close to zero making a small positive incline. In contrast to this overall positive trendline the alpha values between 2019 and 2020 dipped, as seen in Figure 15, in Appendix A.

The determined products of concern *are Metal: catalysts in the form of wire cloth or grill, of platinum*, *Cobalt chlorides*, and *Turbines: steam and other vapour turbines, (for other than marine propulsion), of an output exceeding 40MW*.

Metal: catalysts in the form of wire cloth or grill, of platinum is already an overly efficient system throughout 2012-2020 and has the highest slope for the trendline which indicates that the system will continue to grow more efficient overtime, as seen in Figure 19. *Cobalt chlorides*, and *Turbines: steam and other vapour turbines, (for other than marine propulsion)* have systems that have a slight positive slope; however, these systems have much efficiency to gain, and these values have the second and third highest average alpha value. These efficient systems are brittle and more prone to breakdown in the case of disruption; therefore, these networks will be analyzed in the following section.



LEGEND			
Color	**Product**	**Shape**	**Stage of Value Chain**
🟩	Primary and Refined Cobalt	○	Extraction
🟦	Biomass	□	Processing
🟫	Geothermal Energy	△	Manufacturing
🟨	Solar Energy		
🟪	Electric Vehicles		
🟥	Batteries		

Figure 4: Slope of Trendline vs. Average Alpha Value of Cobalt Products plotted against each other. The border lines for the window of vitality are highlighted with the two red lines (0.32-0.4). The legend is shown above, the color corresponds to the category it is associated with, and the shape is associated with its stage in the supply chain

Table 5: Slope of Trendline and Average Alpha Value for Cobalt Products needed in the Energy Transition. The table is colored using a red-yellow-green gradient, the red values are associated with the highest (most positive) values and the green are associated with the lowest (most negative) values. The table is organized from the most positive

HS	Product Name	Category	Slope of Trendline	Average Alpha Value
711510	Metal: catalysts in the form of wire cloth or grill, of platinum	Solar Energy	0.025491	0.577075
810520	Cobalt mattes and other intermediate products of cobalt metallurgy; unwrought cobalt; cobalt powders	Primary and Refined Cobalt Products	0.010083	0.354468
260500	Cobalt ores and concentrates	Primary and Refined Cobalt Products	0.009687	0.256273
850690	Cells and batteries: primary, parts thereof	Batteries	0.00734	0.362269
840681	Turbines: steam and other vapour turbines, (for other than marine propulsion), of an output exceeding 40MW	Biomass	0.006779	0.387554
282739	Cobalt chlorides	Primary and Refined Cobalt Products	0.004061	0.39186
850650	Cells and batteries: primary, lithium	Batteries	0.002546	0.199682
841869	Refrigerating or freezing equipment	Geothermal Energy	0.000185	0.170918
850440	Electrical static converters	Solar Energy	-0.00118	0.126923
283329	Sulphates of cobalt and of titanium(1988-2500)	Primary and Refined Cobalt Products	-0.00189	0.294371
841899	Refrigerating or freezing equipment: parts thereof, other than furniture	Geothermal Energy	-0.0037	0.201454
841810	Refrigerators and freezers: combined refrigerator-freezers, fitted with separate external doors, electric or other	Geothermal Energy	-0.00379	0.215493
841850	Furniture incorporating refrigerating or freezing equipment: for storage and display	Geothermal Energy	-0.00415	0.185509
841830	Freezers: of the chest type, not exceeding 800l capacity	Geothermal Energy	-0.00418	0.173133
841199	Turbines: parts of gas turbines (excluding turbo-jets and turbo-propellers)	Biomass	-0.00418	0.200396
854140	Electrical apparatus: photosensitive, including photovoltaic cells, whether or not assembled in modules or made up into panels, light emitting diodes	Solar Energy	-0.00464	0.156346
841861	Heat pumps: other than air conditioning machines	Geothermal Energy	-0.00465	0.173926

841840	Freezers: of the upright type, not exceeding 900l capacity	Geothermal Energy	-0.00649	0.19431
841891	Refrigerating or freezing equipment: parts, furniture designed to receive refrigerating or freezing equipment	Geothermal Energy	-0.0065	0.355441
840682	Turbines: steam and other vapour turbines, (for other than marine propulsion), of an output not exceeding 40MW	Biomass	-0.00733	0.353503
870911	Vehicles: electrical, self propelled	Electric Vehicles	-0.02922	0.249234
282200	Cobalt oxides and hydroxides; commercial cobalt oxides	Primary and Refined Cobalt Products	-0.04496	0.346659

4.2 Network Analysis

The network analysis aims to visualize the trade of these products and its changes throughout the last nine-years. Networks are visualized in three-year intervals to see the how the networks have changes in an aggregated time-period. The centrality measures of weighted in-degree centrality, weighted out-degree centrality, and betweenness centrality. The WGI for countries is used to better understand the vulnerabilities of these trading partners. These measures enrich the network analysis and allow for discussion on important nodes within the network. In the network analysis, the three products investigated are listed in a table below. The tables that include the centrality measures, and WGI values for all countries are included in Appendix B: Network Analysis and Appendix C: World Governance Index. Due to how large the networks are, a web-based app was developed so the interactive visualizations could be seen by clicking here.

Table 6: Identified Products of Concern

HS6	Products of Concern	Category	Slope of Trendline	Average Alpha Value
711510	Metal: catalysts in the form of wire cloth or grill, of platinum	Solar Energy	0.025491	0.577075
282739	Cobalt chlorides	Primary and Refined Cobalt Products	0.004061	0.39186
840681	Turbines: steam and other vapour turbines, (for other than marine propulsion), of an output exceeding 40MW	Biomass	0.006779	0.387554

4.2.1 Metal: catalysts in the form of wire cloth or grill, of platinum (HS6: 711510)

The networks for *Metal: catalysts in the form of wire cloth or grill, of platinum* are shown below for the years 2012-2014, 2015-2017, and 2018-2020.

4.2.1.1 2012 to 2014 Network

Germany imported the largest amount of product, accounting for 38.7% of all imports in the three-year period, followed by France, Monaco with 12.5% of imports. Of the top 10 importers, nine are European countries – apart from the United Arab Emirates which accounts for 4.8% of imports.

Similarly, to the imports nine out of the top 10 highest exporters are European countries. Leading is Denmark who accounted for 18.6% of all exports, followed by Czechia at 17%, then the Netherlands at 12.9%. Nine of the 10 highest exporters are European countries, China is the only non-European country ranking as the 10th highest exporter.

In terms of betweenness centrality the countries are more diverse with five of the top 10 being European, however the two highest ranking being from Europe (Germany and the United

Kingdom). This means that Germany and the United Kingdom are the countries which have the most control over the network because that is where the majority of connections are passing through. These are important bridge nodes for the overall network. Important bridge nodes do not need to be high exporting/importing – in this case four of the top 10 nodes of highest betweenness centrality (South Africa, the United States and territories, China, and Republic of Korea) are not in the top 10 highest importers or exporters – this is because these nodes are bridge nodes and are important to connect other nodes to each other on the shortest paths. These are important as disruptions in these countries can cause larger issues in world trade as they facilitate the flow of trade between other countries.

4.2.1.2 2015 to 2017 Network

In the subsequent three-year period (2015-17) Slovakia became the highest importer accounting for 42.6% of all imports. This is followed by France, Monaco with 19.4% of imports, which increased about 7% from the previous three-year period. All top 10 importers during this period are European counties.

The United Kingdom is the highest exporter and accounts for 68.5% of exports in this three-year period, the number of exports increased over 21 times as much from the previous period. This is distantly followed by the Czechia and Denmark accounting for 5.3% and 4.1% of exports, respectively. Seven of the 10 highest exporters are European countries, the non-European countries are: the United Arab Emirates, South Africa, and China.

Of the top ten more important bridge nodes four are from Europe (Germany, United Kingdom, Netherlands, and Italy). This is quite similar to the year before where the two nodes with the highest betweenness centrality are still Germany and the United Kingdom. Eight of the 10 countries are the same as the previous year with the addition of Australia and India and removal of the Republic of Korea and Denmark form the previous network. Germany's betweenness centrality value slightly decreased with an increase in the betweenness centrality value in the United Kingdom and South Africa, meaning they have become slightly more important bridge nodes.

4.2.1.3 2018 to 2020 Network

Accounting for 48.5% of imports Indonesia became the top importer of this time-period. This is distantly followed by the Republic of Korea and Germany with 15.4% and 8.9%, respectively. Eight of the top 10 importers are in Europe, excluding the top two (Indonesia and Republic of Korea). Compared to the countries from the previous period, Indonesia had quite an increase in their number of imports compared to the previous three-year period with its import value being 21 times that of 2015-17, which was 47.4. Indonesia, the Republic of Korea, and Portugal were not previously present in either of the network's top 10 importers.

China is the highest exporter accounting for 48.5% of the exports in this period, where it jumped to the highest exporter from its previous ranking as 9th and 10th in the previous years. The second highest exporter is Australia, who was not previously in the top 10 exporters of the previous years, with 15.5%. Seven of the top 10 exporters are European countries, the non-European countries are: China, Australia, and South Africa.

The most important bridge node is Germany, followed by the United Kingdom and the United States and territories. India, France, Monaco, Bulgaria, and Japan emerged into the 10 highest nodes with betweenness centrality during this three-year period.

4.2.2 Cobalt chlorides (2007-2500) (HS6: 282739)

The networks for *Cobalt chlorides (2007-2500)* are shown below for the years 2012-2014, 2015-2017, and 2018-2020.

4.2.2.1 2012 to 2014 Network

The highest importer between 2012-2014 is the Netherlands, making up 11.9% of all imports, this is followed by France who accounts for 8% of all imports. This is followed by Belgium, Switzerland, and Germany. Saudi Arabia and Hong Kong are the two non-European countries/territories in the top ten highest importers. Saudi is the country with the lowest WGI and the only negative WGI value in the top 10 importers.

The highest exporter in this three-year period is Germany, accounting for 19.9% of all exports, followed by China and Belgium at accounting for 15.3% and 11.1% of all exports, respectively. Six of the countries in the top ten exporters are European countries. The countries with a negative WGI are China, India, and Jordan, in order from most negative to least negative.

The countries with the highest betweenness centrality are Germany, the United States, France, and China. China, India, and Russia are the countries in the top 10 bridge nodes with a negative WGI. Four of the top 10 countries are in Europe (Germany, France, Netherlands, Belgium).

4.2.2.2 2015 to 2017 Network

The highest importer between 2015-2017 is again the Netherlands, accounting for 11.2% of all imports (similarly to the previous period), this is followed by France who accounts for 9.2% of all imports. Seven of the highest importers are European countries. The three exceptions are India, Hong Kong, and Japan, all Asian countries. India has the lowest, and only negative WGI in the top ten importers.

The highest exporter in this three-year period is the same as previous, Germany, accounting for 22.5% of all exports, this is again followed by China and Belgium at accounting for 15.1% and 11.2% of all exports, respectively. Six of the countries in the top ten exporters are European countries. The countries with a negative WGI are China, India, and Jordan, in order from most negative to least negative. This is consistent with the previous three-year period.

The most important bridge nodes are the Netherlands, the United States, and India. China, India, and Russia are the countries in the top 10 with a negative WGI, as in the previous three-year period. The countries that are the most important bridge nodes have remained similar, with eight of the countries appearing on the top 10 bridge nodes from the 2012-2014 period being present in 2015-2017's most important bridge nodes. The two countries that are no longer in the top 10 are the United Arab Emirates and South Africa, these were replaces with Spain and Austria which emerged are some of the top 10 nodes in this period.

4.2.2.3 2018 to 2020 Network

The highest importer between this period is the Netherlands consistent with the previous period, accounting for 8.9% of all imports this is followed by France who accounts for 7.8% of all imports. Seven of the highest importers are European countries. The three exceptions are India, Hong Kong, and the United States. India has the lowest, and only negative WGI in the top ten importers.

The highest exporter in this three-year period is the same as both previous periods, Germany, accounting for 18.7% of all exports, this is again followed by China and Belgium at accounting for 14.1% and 10.5% of all exports, respectively. Seven of the countries in the top ten exporters are European countries. The countries with a negative WGI are China, India, and Jordan, these are also the only non-European countries for this time period, in order from most negative to least negative. This is consistent with the previous three-year period.

The most important bridge nodes are the Netherlands, the United States, and India. China and India are the countries in the top 10 with a negative WGI, consistent with the previous periods except Jordan is not in the top 10 bridge nodes. The countries that are the most important bridge nodes have remained similar, with seven of the countries appearing on the top 10 bridge nodes from the 2012-2014 and 2015-2017’s most important bridge nodes being present in the period. Israel was the only country not included in the previous lists of bridge nodes, South Africa is present in this list of top 10 bridge nodes and for 2012-2014 top 10, and Spain is present on 2015-2017 top 10 bridge nodes along with this three-year period.

4.2.3 Turbines: steam and other vapour turbines (for other than marine propulsion), of an output exceeding 40MW (HS6: 840681)

The networks for *Turbines: steam and other vapour turbines (for other than marine propulsion), of an output exceeding 40MW* are shown below for the years 2012-2014, 2015-2017, and 2018-2020.

4.2.3.1 2012 to 2014 Network

The highest importer between 2012-2014 is South Africa, making up 42.6% of all imports, this is followed by Brazil who accounts for 17.1% of all imports. Indonesia and Turkey distantly follow, accounting for about 5% each of all imports. Main importers other than the United States and Republic of Korea, which have a higher WGI, have a WGI between -0.6 and 0.29. `

The highest exporter within this time frame is China, who accounts for 30.2% of all exports, this is followed by Poland who accounts for 14.3% of all exports, and closely followed by Germany who accounts for 12.3% of all exports. Half of the top 10 exporters are European countries and account for 35.4% of all exports. China, which is the highest exporter, has the lowest WGI of the top 10 exporters at -0.49. Eight of the ten have a positive WGI value, with China and Czechia with a negative value.

The most important bridge nodes are the United States and territories, and South Africa. This is followed by China and Germany.

4.2.3.2 2015 to 2017 Network

The highest importer between 2015-2017 is again South Africa, increasing their imports to 84.6% of all imports, this is followed by Turkey who accounts for 3.9% of all imports. Other top importers account for less than 1% of imports. Making South Africa the largest importer by far during this time period, with a WGI of 0.29.

The highest exporter within this time frame is the Netherlands, which account for 70% of all exports, followed by Germany which steadily accounts for 11.2% of exports, then distantly followed by China, Poland, and Japan which make up 5% or less of exports each. Half of the top 10 exporters in this time period are European countries. Russia and China have negative WGI values, -0.71 and -0.49, respectively. All other top exports have a positive WGI value above 0.7.

The most important bridge nodes are South Africa, the United States, and Germany. South Africa and Germany keep their spots as most important bridge nodes. South Africa, China, and Turkey are the bridge nodes with the lowest WGI values, with the latter two being negative.

4.2.3.3 2018 to 2020 Network

The highest importer in this time period is again South Africa, greatly reducing their imports and now accounting for 17.9% of all imports, this is followed by Turkey who accounts for 16.9% of all imports. Followed by Indonesia, Bolvia, and China which account for about 12% of imports each. All major importers, excluding South Africa, Japan, and the United States have a negative WGI value.

The highest exporter within this time frame is China, which is responsible for 29.4% of all exports, followed by India which accounts for 16.6% of all exports. China increased its exports from the last 3-year period and is again the highest exporter similarly to the first three-year period (2012-14). China, India, Pakistan, and Brazil have a negative WGI value.

The most important bridge nodes are the United States, Germany, and China. China and India are the two bridge nodes with a negative WGI, all other nodes have a positive WGI. Four of the top ten bridge nodes are in Europe.

5 Discussion

5.1 Results

5.1.1 Resilience of Products

This section will mainly explore the interesting results related to primary/refined cobalt, lithium-ion batteries, and electric vehicles. The focus on these products is important due to their current and future importance in the cobalt market.

Two of the three highest slope values belong to primary and refined materials, meaning that these product's data presents an upward trend or increased efficiency overtime. Increasing redundancy in the supply chain in terms of sourcing is difficult to diversify, because for primary material deposits need to be found in a new location or to diversify refined cobalt countries need to take the initiative to build partnerships with sourcing agents and build infrastructure for refinement. However, van den Brink et al. (2020) explains although cobalt is highly concentrated at the country level there is diversity in the mined supply due to an estimated 80 artisinal mines, which reduces some of the supply risks. The average resilience of primary cobalt reflects this as it is resilient.

Lithium Ion Batteries and Electric Vehicles are extremely important to the cobalt market, due to their high market share. In 2021 growth was led by lithium-ion battery applications, accounting for 63% of annual demand and 85% of year-on-year growth (Cobalt Institute, 2021). Both battery products have a positive slope, for both products the systems had a higher alpha value in 2019 than 2018, then in 2020 the alpha value was less than 2019. However, the lithium batteries have maintained a system that has been overly redundant throughout the nine-year span. This system hit a maximum value of 0.28 for its alpha in 2019, seen in Figure 15. This 'peak' in 2019 could be due to the performance growth of most Chinese lithium battery material companies. That year it was less than expected and the performance of most companies declined year-on-year (China Battery Enterprise Alliance, 2020). Their downstream demand was affected due to a decline in financial subsidies for new energy vehicles and demand for power batteries decreasing (China Battery Enterprise Alliance, 2020). Although the market supply had increased overtime there the companies were affected by intensive market competition and declining product sales or prices.

Electric vehicles only had four years of available data for analysis. The COVID-19 pandemic impacted the data from 2020, affecting ¼ of the available data points. This is important to note as compared to other products there is not as much historical data. However, electric vehicles have had an overly redundant network for all available years. In 2021 they became the largest end user of cobalt and have the largest growth potential (Cobalt Institute, 2021).

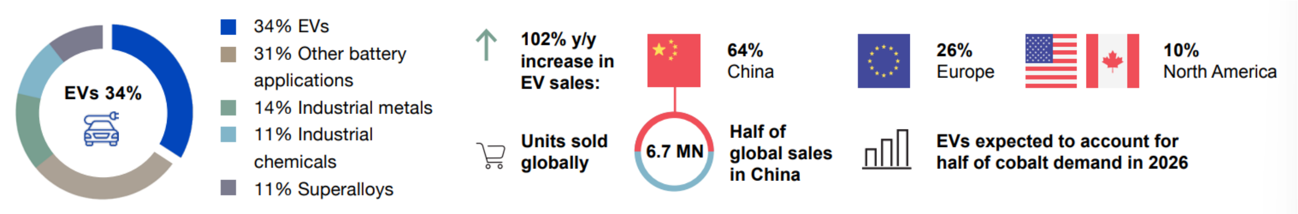


Figure 5: Electric Vehicles 2021, Source: 'Infographic Cobalt Market Report 2021' (Cobalt Institute, 2021)

All products, except for *Metal: catalysts in the form of wire cloth or grill, of platinum*, had a slope with an incline of less than 0.01. Most products had slopes between -0.01 and 0.01, this indicates little change in the resilience for the majority of cobalt products over the last nine years.

5.1.2 Products of Concern

This section will mainly explore the interesting results related to vulnerable products.

5.1.2.1 Metal: catalysts in the form of wire cloth or grill, of platinum (HS6: 711510)

The product with the most efficient network and highest slope of the trendline was *the Metal: catalysts in the form of wire cloth or grill, of platinum*, which is used for solar energy products. In this network European countries held an important role as importers, exporters, and bridge nodes. The most important bridge nodes are Germany, the United Kingdom, and the United States, and territories. These three countries have held spots as the four most important bridge nodes throughout all time periods, with the top two consistently being Germany and the United Kingdom, respectfully. Many of the major players throughout the years, other than China, Indonesia, and Bulgaria, have a high WGI value. The WGI for China and Indonesia is -0.49 and Bulgaria's is 0.18. The situations with these more vulnerable partners, from a world governance perspective, should be observed and stability in governance and trade should be of utmost importance to their trading partners as the network is already so vulnerable to supply chain shocks. There should be efforts from countries who are planning to expand their solar production, such as the United States who has recently passed a bill which would rapidly expand solar projects, to try to find ways to build resilience in these global supply chains or secure a domestic production of this product (Woody, 2022).

From 2018-2020 Indonesia and China became leaders in trade, where Indonesia was responsible for 1007.249 tons of imports and China exported 1007.371, based on the trade data it is observed that almost all Chinese exports are sent to Indonesia. China is building partnerships with Indonesia as they have raw materials needed for the supply chain of batteries. They have invested billions of dollars into Indonesia for nickel and cobalt projects. In 2018 GEM Co Ltd invested $700 million USD in a project that expected 4,000 tons of cobalt smelting capacity and produce a range of battery chemicals (Cottle, 2022). In 2021 Huayou invested $2.1 billion USD in 2021 for their third nickel project in Indonesia to produce 120,000 tons of nickel and 15,000 tons of cobalt annually on a metal content basis (CNBC, 2021). China is the main refiner of cobalt, and their manufacturing hubs allow them to vertically specialize and retain the value added from imported primary cobalt, interestingly as they gain more primary material from Indonesia, they seem to increase exports of metal catalysts. The Cobalt Institutes 2021 market report has been identified Indonesia as the largest growth market for refined cobalt production after China, despite only starting to produce refined cobalt in 2021. They are expected to provide ¼ of total refined cobalt and 32% of refined chemical growth (Cobalt Institute, 2022).

Indonesia set out to reduce greenhouse gas emissions by 29-31% by 2030 (Republic of Indonesia, 2021). With this, Indonesia is clearly increasing their portion of renewables into their energy production. Solar is becoming a more popular renewable option in Indonesia as the barrier to entry for solar projects has been high as they are very expensive for this region. In Indonesia solar PV activity has generally been in the form of small and medium-size projects, however in 2019 the largest solar PV project was commissioned, a 21 MW plant (International Energy Agency, 2020). This explains the increased imports in the 2018-2020 time period. In 2021 Indonesia received a boost in government support in the renewable energy sector where they are on course to become a major exporter of solar power (Murtaugh, 2022). This all indicates that trade partnership between China and Indonesia will remain strong within the coming years as Indonesia will require more supply of metal.

5.1.2.2 Cobalt chlorides (2007-2500) (HS6: 282739)

The network results for cobalt chlorides were very consistent throughout the time periods. Over half of the top 10 importers/exporters are European countries throughout the three networks. Within the nine years of trade China India and Jordan are the only non-European exporters – these countries also have a low average WGI value. Hong Kong was a top importer throughout, and China was a top exporter throughout – most of the imported cobalt to Hong Kong is from China. It can be reasonably assumed that China and Hong Kong would have a strong trade relation due to history and proximity, however it is still an interesting finding that could prompt further investigation. The consistency of this network throughout the years is high as the trade partners haven't changed much over the last ten years and the resilience being similar throughout the nine-year period, seen in Figure 11 . Even the most important bridge nodes have remained similar, with seven of the countries appearing on the top 10 bridge nodes reoccurring for all time periods. Effort can be brought to make the network more resilient as the main concern is that it has efficiency to gain that will push it out of the 'window of vitality' and can make it a potential cause for concern.

5.1.2.3 Turbines: steam and other vapour turbines (for other than marine propulsion), of an output exceeding 40MW (HS6: 840681)

The highest importer was South Africa for all time periods, they accounted for 42.6% of all imports in 2012-2014, in 2015-2017 they accounted for 84.6% of all imports, then significantly reduced their share of imports to 17.9% from 2018-2020. China was the largest exporter in 2012-2014 and 2018-2020 accounting for about 30% of all exports, however, interestingly the Netherlands became the largest exporter in 2015-2017 accounting for nearly 70% of all exports. The Netherlands went from exporting 1020.638 tons in 2012-2014, to 397189.92 tons in 2015-2017, and 2906.774 in 2018-2020. This information shows the rapid changes in trade for this network, as South Africa's market share decreased significantly, and the Netherlands jumped quickly in production between 2015-2017. Additionally, the most important bridge nodes throughout are geographically scattered, from the United States to South Africa, China, Europe, Guatemala, and Saudi Arabia. This network is less consistent than that of cobalt chlorides for instance, therefore future trends for purchase of these turbines should be studied to understand how the supply chain will develop. This product is also within the window of vitality based on the average nine-years of trade; however, the slope shows a slight increase and in 2020 the alpha value was 0.47, being quite efficient.

5.2 Current Supply Chain

Cobalt is an interesting material as it is mainly controlled by two countries, the DRC and China. The DRC is the world's largest supplier of cobalt, being responsible for 74% of the mined supply in 2021 (Cobalt Institute, 2021). There is little to no vertical specialization in DRC leading to negligible benefits from the value chain. The DRC has had issues with child labor and modern slavey; however, a small amount of cobalt mining is currently linked to these problems- although it has garnered international attention. However, as cobalt mining intensifies these issues may be exacerbated, causing exploitation and violence against vulnerable peoples. As cobalt prices increase this entices people to join the mining sector. As a result, the artisanal mining supply will be even stronger and account for a larger share of both DRC and global mined supply (Cobalt Institute, 2022). Currently, the DRC is looking to move away from this negative image and formalize the artisanal mining sector which will help solve a lot of the countries "bad PR" when it comes to cobalt.

As of 2020 China owned 15 of the 19 cobalt-producing mines in the DRC (Lipton & Searcey, 2022). Additionally, 64% of cobalt is refined in China (Mining, 2021). There is no possibility of discussion to the future of cobalt without the DRC and China as they have and will continue to have a dominance on the market for the foreseeable future (Mining, 2021). This causes serious geo-political implications, with instability in the DRC government and the increasing global power of China. Both of which do not rank highly based on their average WGI, Appendix C contains all WGI averages.

The United States and Europe have shown concern over this dominance, near monopoly, in the supply chain. Tiffin Caverly, vice president at the Export-Import Bank of the United States, was quoted saying *China has a sort of a stranglehold on the supply chain*, and that they had concerns about how to break this advantage China has created with their long running history in securing CRM in the DRC (Lipton & Searcey, 2022). Similar concerns have been brought up by Thierry Breton, EU's industry commissioner, who called China the EU's systemic rival in the *true global race* of sourcing and recycling of CRM (Breton, 2022). The United States and China recognize the importance of cobalt to energy, security, and defense needs and that they have catching up to do with China's large advantage (Peel & Sanderson, 2020).

However, China does not allow for the United States or the EU to make significant advancements to compete in this global race. Chinese companies have spent billions (USD) trying to buy out the United States and Europe in the DRC for over a decade (Ahlijian, 2020). China has already built long-lasting relationships with the DRC and has heavily invested in their country, while expecting them to fulfil their cobalt needs. The need for Chinas increasing demand for cobalt was due to its input in lithium-ion batteries. Its domestic mine production was unable to provide enough primary cobalt, at an economically feasible price due to inadequate supply, to grow the refining industry that was in place. Therefore, China was unable to meet their domestic manufacturing targets with their supply, which triggered the Going Out Strategy in 2000 (Gulley et al., 2019). This strategy encouraged overseas foreign direct investment that products and transported minerals critical to China's strategic development plan, this led to the 'minerals and infrastructure deal between China and the DRC (Gulley, McCullough, & Shedd, 2019). Analysis have argued that China's overseas foreign direct investment is as a tactic to limit the supply for competitors, ergo leaving them dependent on China and constrained in the short-term (Gulley et al., 2019)

This claim supports fears about securing supply from the United States and EU, which are increasing their consumption of cobalt products rapidly due to the rise of the electric vehicle and batteries. This demand for products will only grow within the coming years. It is estimated by 2030, 30 million electric cars are expected to be on the roads in the EU with an equal number of batteries to be produced, with help from the green recovery policies and subsidies post COVID (Breton, 2022). The United States has nearly doubled their EV sales in 2021 and there is hope that increased policy support will allow them to catch up with Chinese and European EV markets, as seen in Figure 7 (Cobalt Institute, 2022). EVs alone will drive around 70% of this growth with other battery applications contributing 20%. By 2026, EVs will account for half of cobalt demand (Cobalt Institute, 2022).

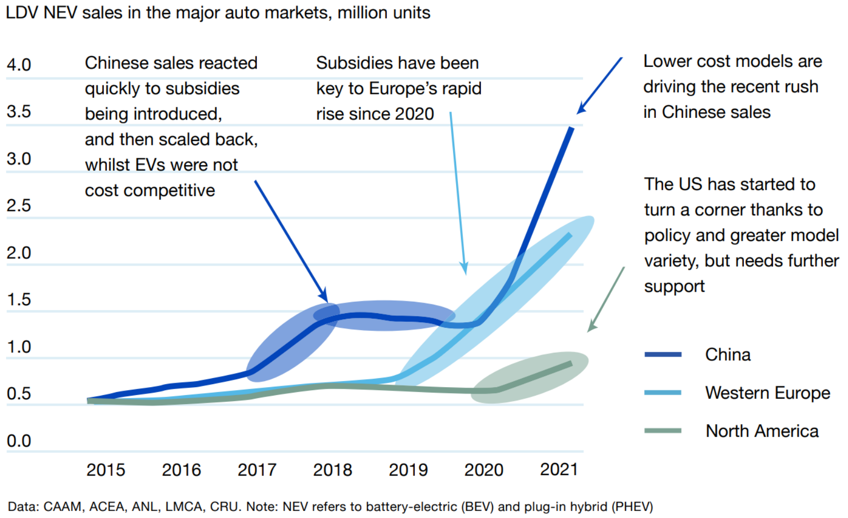


Figure 6: Electric Vehicle Trends from 2015 to 2021, Source: 'Cobalt Market Report 2021' (Cobalt Institute, 2022)

This information aims to show the difficulty that there is to diversify the supply chain, due to the strong hold on it by China. Although other governments have tried to compete, they have been unsuccessful due to Chinas long standing relationship with DRC and Africa in general. China has vertically specialized, and they only stand to lose economically from giving away some control they have on the supply chain. As they have managed to retain a supply of products to satisfy the domestic market as well as to create a market for export.

Other countries can look to build partnerships with the DRC and follow in China's footsteps, however, it is difficult to know whether that will prove as successful due to Chinas control over mines. During the Cobalt Conference 2022, in Zurich Switzerland, the representatives from Zambia (Hon. Paul Kabuswe, Minister of Mines and Minerals Development, Republic of Zambia) and the DRC (His Excellency Julien Paluku Kohongya, Minister of Industry, Democratic Republic of Congo) shared their interest in foreign investment to export the cobalt belt that stretches from the DRC to Zambia. Zambia's representative spoke about the potential that their land has and how it can be beneficial for both their own country as well as investors. However, their true goal for investment is to explore land and help build a continent-wide battery value chain so that Africa gains from the benefits of their natural resources; this could create an opportunity for competitors to try and invest in the exploration of new sources for refined products, intermediate products, and finished products. According to the 2021 Cobalt Market Report, supply side investment remains critical to ensure sufficient supply into the longer term as cobalt demand continues to rise even higher. However, from a domestic perspective looking into circularity may a good way for countries to begin to offset some of their import reliance on these CRM.

5.3 Research Limitations

This thesis analyzed cobalt products for the energy transition. The intermediate and final products were mainly based on the International Centre for Trade and Sustainable Development list of cobalt products which was comprised of the first 4 digits of the HS6 codes and led to finding products in solar, geothermal, and biomass. However, there are other energy sources that are neglected that use cobalt products, such as wind energy. HS6 codes for products needed in the energy transition were not found, therefore this limited the exhaustiveness of the products available for research.

5.4 Future Research

Other than the previously mentioned limitations, and some interesting results to consider for research, there is more research that can be considered.

Using the same methodology there should be an exploration of more products needed for the energy transition, considering different CRM. Additionally, there should be studies looking into recovery of the supply chain of cobalt products after a disruption, a method to explore using would be the Cox PH function. Future disruptions such as wars, trade wars, pandemics, and other situations that would apply strain to the global supply chain should be modeled to see the effects and prepare to strengthen networks. Considering that the trade data was only available until 2020 it was not possible to see the recovery of the supply chains from COVID-19; this would also be an interesting point for future research.

In terms of securing access to cobalt should be research into how other countries can build partnerships with cobalt rich nations and how/if other countries can compete with China’s control of cobalt. There should also be more research looking into scenarios, methods, and technology for securing CRM using circular practices. More effective methods of collection of cobalt containing components such as e-waste and electric vehicles should be researched.

Based on the results regarding the products of concern it is apparent that European countries also have a stronghold as top importers, exporters, and bridge nodes. These important European countries rank positively on the WGI and therefore are not a high risk based on governance. Therefore, attention should be brought to these vulnerable products and exploration should be done on how to increase the resilience of these networks.

6 Conclusion

This study used ENA to analyze the resilience of nine-years of trade data (2012-2020) for cobalt products needed for the energy transition. The resilience is measured using an alpha indicator which considers both the efficiency and redundancy of a network. More efficient products are vulnerable to supply chain shocks due to their lack of diversity in pathways. The networks which are considered to have an equal balance of both efficiency and redundancy are located within the window of vitality, where products outside this window are considered to have overly efficient or redundant networks. Based on how efficient (or vulnerable to supply chain shocks) the systems are on average, measured by the average of the nine-years of alpha values per product, and the efficiency the products stand to gain, based on the slope of their trendline, three products of concern are identified. The directional weighted networks of these products of concern are visualized. Centrality measures are taken to identify the top exporters, importers, and bridge nodes. International trade can become highly vulnerable due to many factors, one of them being the governance of the trading partners; therefore, to compliment the analysis WGI values are taken to understand the stability trading partners.

The results showed that primary cobalt, *Cobalt ores*, are considered to have overly redundant systems and have a slope of 0.01, which can push that into the window of vitality, however once that happens there should be adjustments so that the system does not become too efficient. There are limited sourcing agents, and the system may continue to become overly efficient if resilience follows the pattern of the trendline. Entities that regulate and facilitate international trade, large sourcing agents, renewable energy companies, governments, and all other stakeholders in the cobalt supply chain should be and are already aware of this. Action can be taken to build partnerships with sourcing countries as well achieving diversity in mining locations and of agents within mining locations, such as those produced by artisanal mining. However, this artisanal mining should be legal and done in a way that respects human-rights. Other avenues such as deep-sea mining can be explored, however, more research needs to be done on its environmental impacts and impacts of sea mining to the local economies.

Three of the four refined cobalt products (in the processing stage of value chain) are located within the window of vitality; however, *Cobalt chlorides* will soon be pushed out of this window and into an overly efficient system. This product was identified as one of the products of concern. Generally, for refined cobalt products, China has a large influence on the supply chain due to their strong ties with the DRC and ownership of mines there. These connections guarantee an influx of primary material, making them large exporters of refined cobalt; China is one of the top exporters of cobalt chlorides throughout the nine-year analysis period. The network results for cobalt chlorides were very consistent throughout and research should be put into make the network more resilient as the main concern with this network is that it has efficiency to gain.

Two of three biomass products are in the window of vitality, with *Turbines: steam and other vapour turbines, (for other than marine propulsion), of an output exceeding 40MW,* becoming overly efficient as time continues. Attention should be put into strengthening the resilience of this global supply chain, Countries looking to generate more biomass energy should looking into manufacturing their own turbines.

Geothermal energy is mainly overly redundant with all but one of their products, which is in the window of vitality. Over the past nine years these products show networks which are resilient and less prone to breakdown over supply chain disruptions due to the diversity of their connections.

Two of the three solar products are overly redundant. However, *Metal: catalysts in the form of wire cloth or grill, of platinum* is a solar product of great concern due to its high average alpha value and high trendline. The network for this product is limited in its number of connections and makes it extremely vulnerable if there is an issue in the supply chain. There are increased investments in solar globally, within Indonesia and more recently in the U.S. who passed its largest climate bill which contribute heavily to the expansion of solar energy. If there is no viable alternative found for metal catalysts, there can be a huge issue for the expansion of solar projects globally. The network for this product is currently the most efficient and the one with the highest slope for its trendline. Attention should be put on building domestic manufacturing and strengthening the global supply chain from countries looking to build their solar energy.

Electric vehicles have had a system which has been resilient for the three years of available data, this product has overtaken the cobalt market as the largest exported product. The resilience of its system and low slope value is promising as the system has a large diversity of connections. However, it should be noted that systems which are highly redundant can become highly stagnant. For batteries, *Cells and batteries: primary, parts thereof* is in the window of vitality with a slope value below 0.01, this product can be pushed out of the window of vitality if attention is not placed on the supply chain within the coming years to make sure it is remains stable rather than gaining efficiency. *Lithium-Ion batteries* are in an overly redundant system with a relatively low positive slope; therefore, these systems are and will be less susceptible to supply chain shocks in the next few years if the trend continues.

This research is all aimed to an evaluate of cobalt products needed for the energy transition by answering the research question:

Is the global supply chain of cobalt jeopardizing the energy transition?

This main research question can now be answered using the analysis of resilience and the trade networks of vulnerable products.

In conclusion, the current supply chains of cobalt products are not currently jeopardizing the energy transition, with the exception of solar energy - due to *Metal: catalysts in the form of wire cloth or grill, of platinum*. This is all to say that overall, the products needed for the energy transition have a near constant resilience over from 2012-2020 and an average alpha value lower than the optimal alpha value, indicating on average overly redundant networks. Therefore, most products for the energy transition have networks over the past nine-years which are more resilient to supply chain shocks and maintain a consistent alpha value, or level of resilience.

The products of concern are heavily influenced by European Countries, China, and the United States, these countries were the in the list of highest importers, exporters, and most important bridge nodes throughout all nine-years. For *Metal: catalysts in the form of wire cloth or grill, of platinum* China heavily grew its export capacity and was the highest exporter in the 2018-2020 network, showing the dominance China has over this product. China stayed consistent as the second highest exporter, after Germany, contributing to 15% of total exports for *Cobalt chlorides*. China was also the highest exporter for steam turbines in 2012-2014 and 2018-2017, coming in as third highest exporter in 2015-2017 for *Turbines: steam and other vapour turbines (for other than marine propulsion)*. The United States and the European countries that are important for vulnerable products have a high WGI value, indicating that they have strong governance. In contrast, China has a low WGI which indicates weaker governance, which can cause issues of supply due to trade interruption from potential governance issues (i.e., political unrest). This is cause for attention as they are heavily involved in supplying these products and China is recognized to continue playing a major role as an exporter.

This study can be used as a launch pad to begin more research on supply chain resilience of products (containing CRM) for the energy transition and more research on global trade networks using ENA. The networks and resilience information be used as a basis of knowledge as to what the historical information for these products is and their predicted trends for resilience. This can be compared to their future networks in hindsight and can be used to predict the resilience of products in the coming years.

6.1 Advice for Decision Makers

This study aims to inform individuals involved in the energy and transportation, industry, relevant government officials (mining and industry departments), cobalt stakeholders (at all points in the supply chain), and researchers. Governments and recyclers can make investments and organizations and universities can research methods to improve circularity to reduce dependence on imports. Governments and industry can find ways facilitate infrastructure/production of some of these vulnerable intermediary or final products by importing the raw/refined material from China. Decision makers are now aware of products which have had an overly efficient network and a high slope for their trendline. This historical information is important as it has showed us what networks resilience have looked like before instances of major disruption. Efforts should be placed into adapting the current supply chain management strategies to account for potential supply chain disruptions and use other strategies that are not just in time for renewable energy companies. Once products are in the window of vitality efforts should be made to keep them there to ensure a balance between resilience and efficiency within the global trade network. More importantly, countries should look to secure their own access to primary/refined cobalt from diverse sources, if countries are able to do this then they can domestically handle manufacturing of their own products and there will be less issues in securing access to cobalt and there will be less of a monopoly on the supply chain.

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Appendix A: Detailed Alpha Value Analysis

Below is a more detailed look at the resilience of cobalt products over the past nine years.

6.1 Primary and Refined Cobalt Products

The graphs below, Figure 7 and, shows the alpha values over the past nine-years for primary and refined cobalt products. The products that pertain to primary and refined cobalt products will be discussed individually.

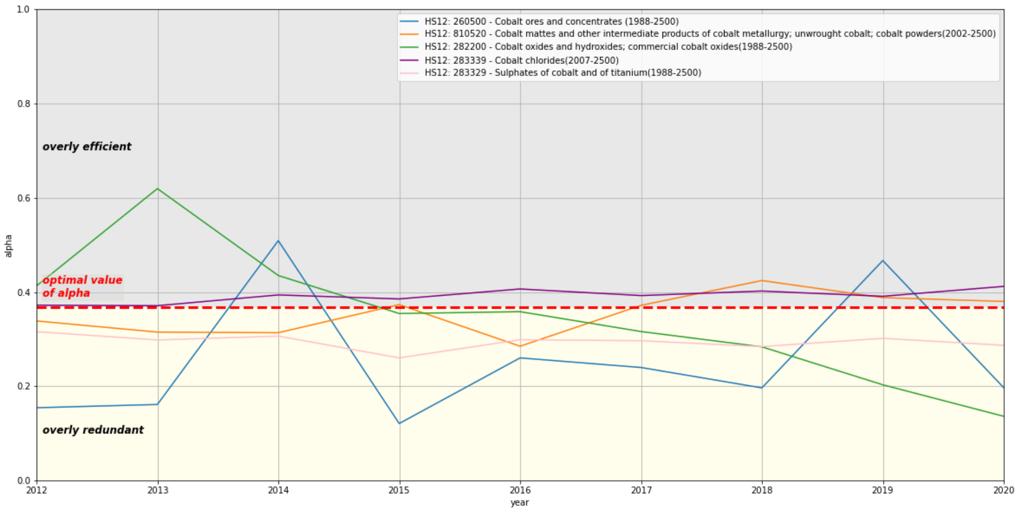

Figure 7: Primary and Refined Cobalt products

6.1.1 Cobalt ores and concentrates (HS6: 260500)

This product has fluctuating alpha values throughout the years. For the first two years it was consistent then it increased from 0.161 in 2013 to 0.509 in 2014. The alpha value remained below the optimal alpha until 2019, where it increased to 0.467. The alpha values seem to fluctuate for this product throughout the years, with a maximum value of 0.509 in 2014 and a low of 0.121 the subsequent year. In Figure 8 below the data points are shown along with the linear trend line. The linear trend line was used to calculate the overall slope of the line. In this case the slope is positive (0.0097) and most of the data points are below the alpha value making the trade networks for these years overly redundant. However, the trendline shows that there is an overall positive trend for these historical alpha values.

Table 7: Alpha Values (HS6: 260500)

Alpha	Year
0.154427	2012
0.161345	2013
0.50912	2014
0.1209	2015
0.260232	2016
0.239862	2017
0.196582	2018
0.466903	2019
0.197087	2020

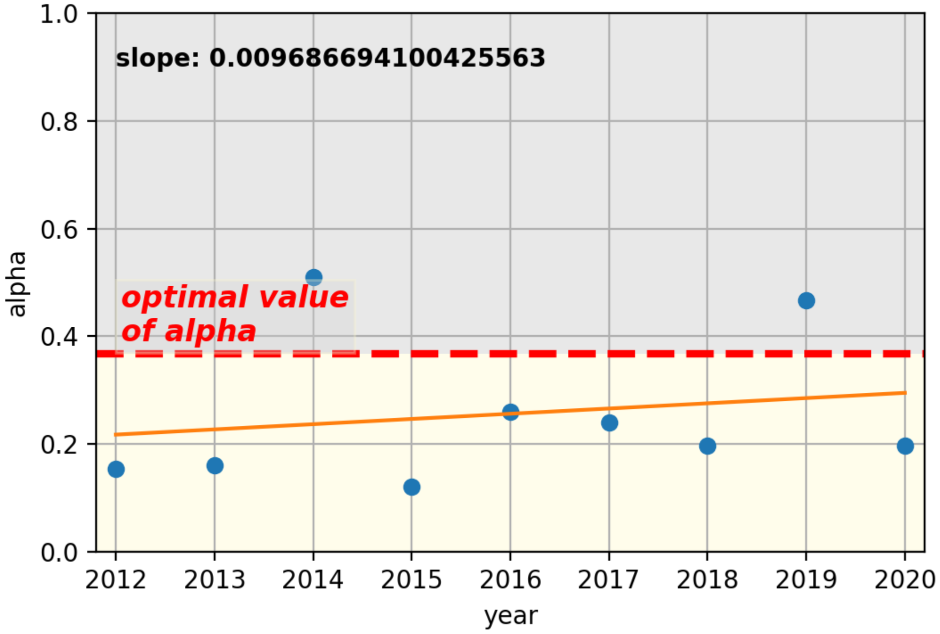

Figure 8: Trendline (HS6: 260500)

6.1.2 Cobalt mattes and other intermediate products of cobalt metallurgy (HS6: 810520)

This product alpha values throughout the past nine-years have remained between 0.1 of the optimal alpha value. The highest alpha was 0.424 in 2018 and the lowest alpha was in 0.285 in 2016. In the last three years (2016-18) the average alpha value (0.398) is higher than the average alpha value (0.322) of first three years (2012-14) by 0.075. This essentially shows that the network is more efficient the last three years versus the first three meaning the network is more vulnerable to supply chain shocks the last three years. In Figure 9 the data points are shown along with the linear trend line. The linear trend line was used to calculate the overall slope of the line. In this case the slope is positive (0.0101) and most of the data points are below the alpha value making the trade networks for these years overly redundant.

Table 8: Alpha Values (HS6: 810520)

Alpha	Year
0.33868	2012
0.315009	2013
0.313723	2014
0.373348	2015
0.284982	2016
0.371777	2017
0.42445	2018
0.388149	2019
0.380094	2020

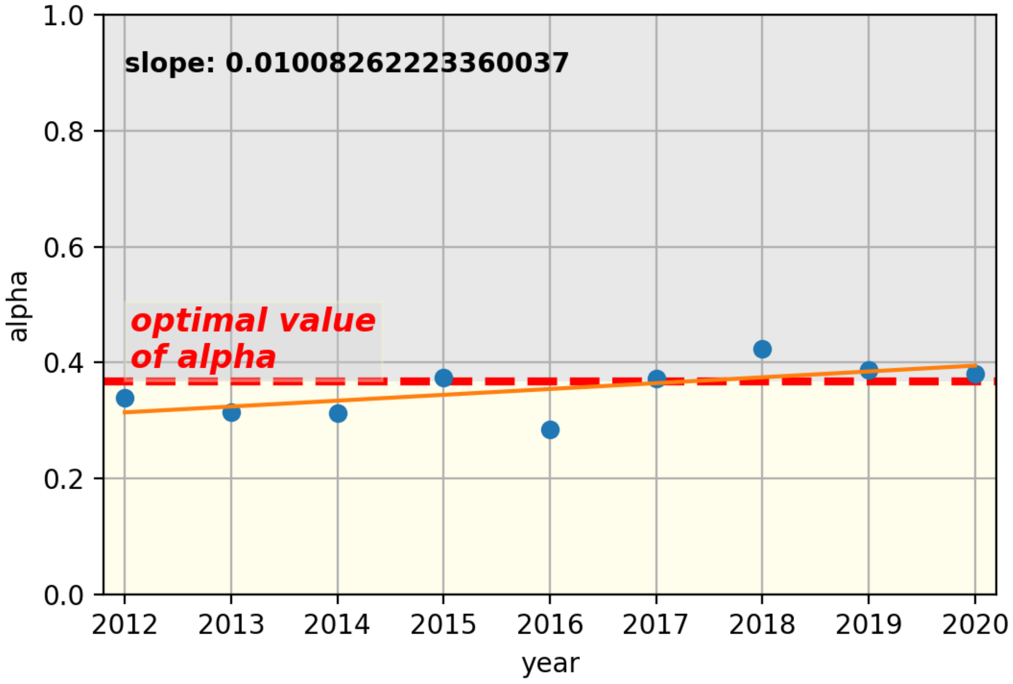

Figure 9: Trendline (HS6: 810520)

6.1.3 Cobalt oxides and hydroxides, commercial cobalt oxides (HS6: 282200)

This product has had most of its values below the optimal alpha value making most of the trade networks over the nine-year time span overly redundant or less vulnerable to supply chain shocks. Initially the supply chain alpha value increased in 2013 as compared to the previous year (2012) by 0.2, following those years there was a steady decline in alpha with the lowest value of 0.136 in 2020. In analyzing the linear trendline, shown in Figure 10, the slope is negative at -0*.045* which shows that tendency of the data tends to be more redundant overtime, making the network less vulnerable to supply chain shocks overtime.

Table 9: Alpha Values (HS6: 282200)

Alpha	**Year**
0.413042	2012
0.619635	2013
0.43508	2014
0.35445	2015
0.35837	2016
0.316205	2017
0.283717	2018
0.203156	2019
0.136272	2020

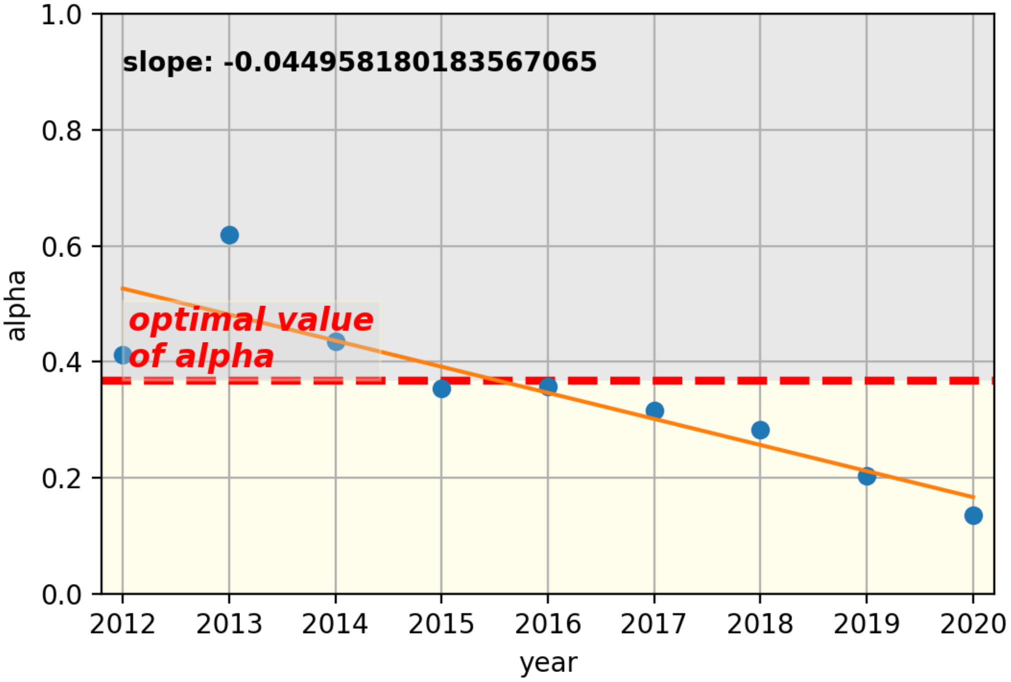

Figure 10: Trendline (HS6: 282200)

6.1.4 Cobalt chlorides (HS6: 282739)

Throughout the past nine-years the values for cobalt chlorides have been above the optimal alpha value. However, these values hover quite close to it ranging from its lowest at 0.371 in 2013 to its highest 0.412 in 2020. The slope of the linear trendline for this product is 0.0041, which creates a relatively flat trendline with a slightly upward slope – meaning efficiency is slightly increasing overtime.

Table 10: Alpha Values (HS6: 282739)

Alpha	**Year**
0.372047	2012
0.37106	2013
0.393905	2014
0.385382	2015
0.406551	2016
0.392564	2017
0.40215	2018
0.391003	2019
0.412083	2020

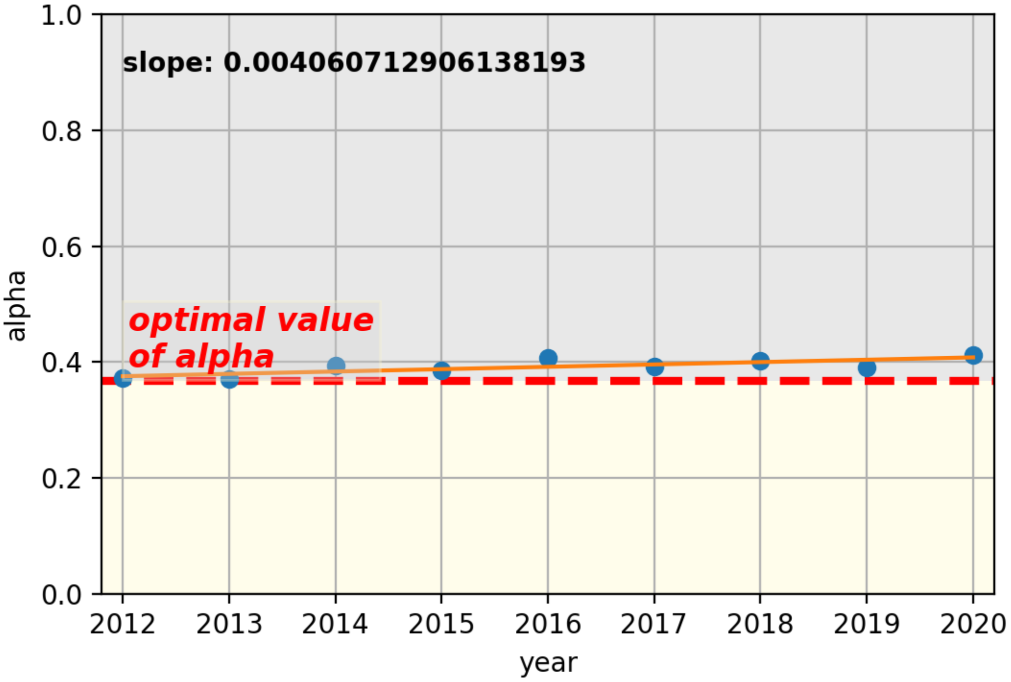

Figure 11: Trendline (HS6: 282739)

6.1.5 Sulphates of cobalt and of titanium (HS6: 283329)

This product has had alpha values lower than the optimal alpha value throughout the years. The alpha values have stayed relatively consistent with the highest value being 0.316 in 2012 to the lowest being 0.260 in 2015. The slope for this line is -0.0019, which is nearly flat with a negative slope indicated the trend based on this historical data is the network becoming slightly more redundant overtime.

Table 11: Alpha Values (HS6: 283329)

Alpha	Year
0.315855	2012
0.298317	2013
0.306499	2014
0.260254	2015
0.298793	2016
0.296646	2017
0.284269	2018
0.301769	2019
0.286935	2020

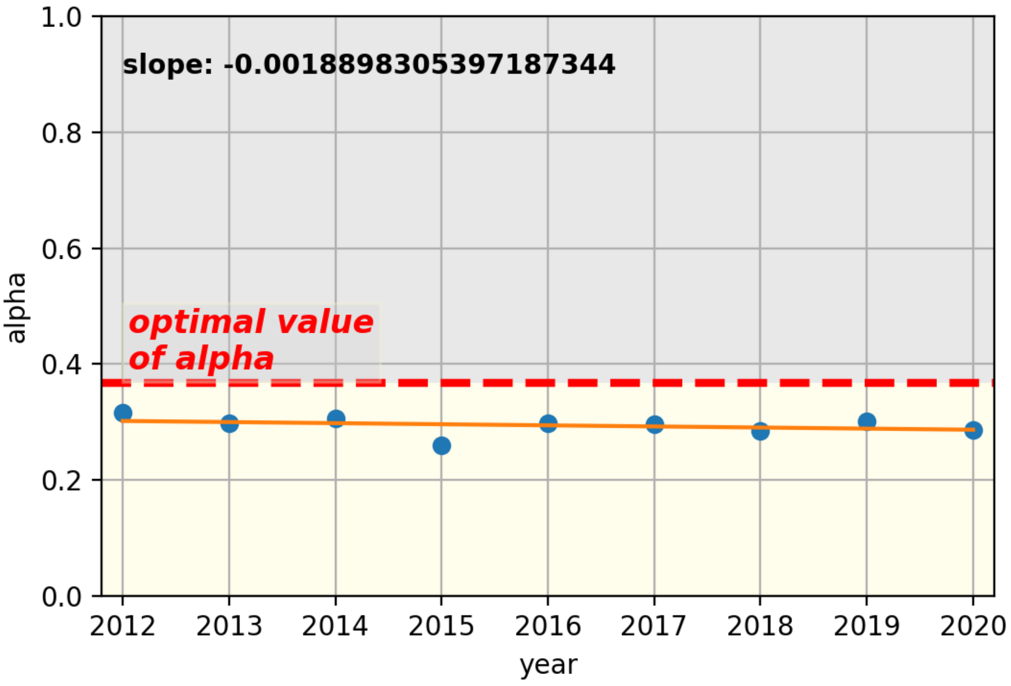

Figure 12: Trendline (HS6: 283329)

6.2 Batteries and Electric Vehicles

The graphs below, Figure 13 and Figure 14Figure 7, shows the alpha values over the past nine-years for batteries and electric vehicles. The products that pertain to batteries and electric vehicles will be discussed individually.

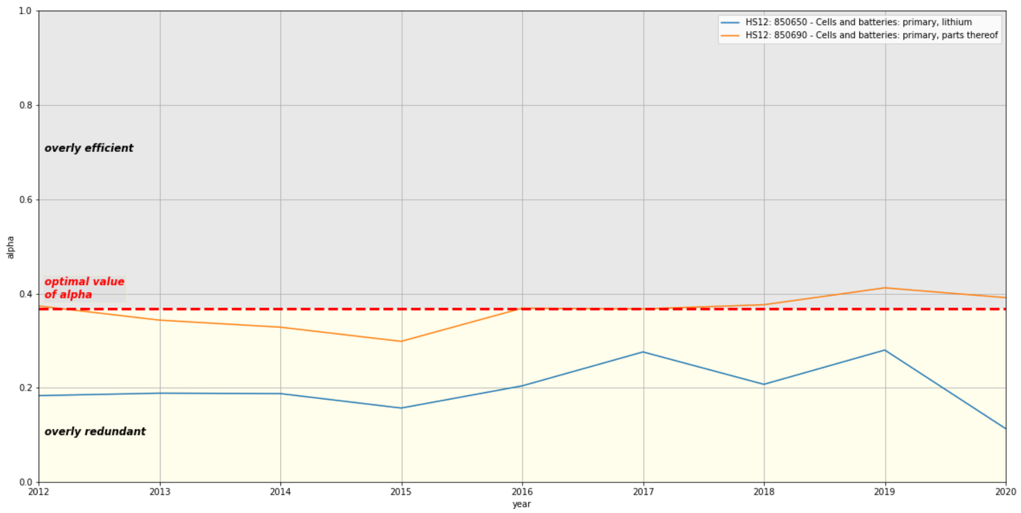

Figure 13: Batteries

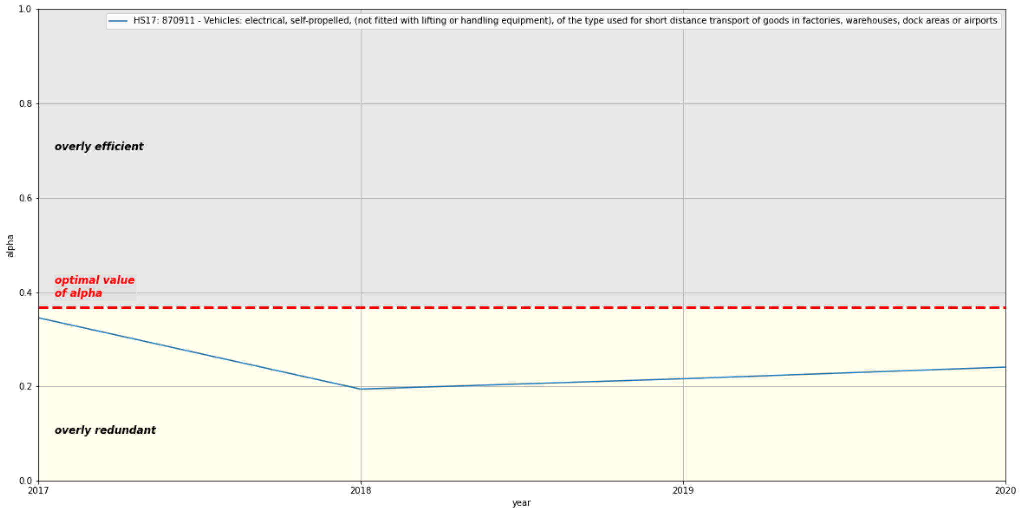

Figure 14: Electric Vehicles

6.2.1 Cells and Batteries: primary, lithium (HS: 850650)

This product has all values below the optimal alpha value which points to a consistently overly redundant trade network. The alpha values slightly fluctuate throughout the years with a high of 0.280 in 2019 and a low of 0.113 in 2020. The trendline, however, is quite flat with a slope of 0.0025 indicating a minor upward trend to the line. However, the slight positive trend is mainly due to the higher alpha values in 2017 and 2019 most of the alpha values are relatively clustered within about 0.03 of each other. The LI battery is one of the most demanding sectors in terms of cobalt and that will continue to grow in demand in the coming years.

Table 12: Alpha Values (HS: 850650)

Alpha	Year
0.183279	2012
0.18857	2013
0.187635	2014
0.156944	2015
0.204036	2016
0.276066	2017
0.207326	2018
0.280058	2019
0.113224	2020

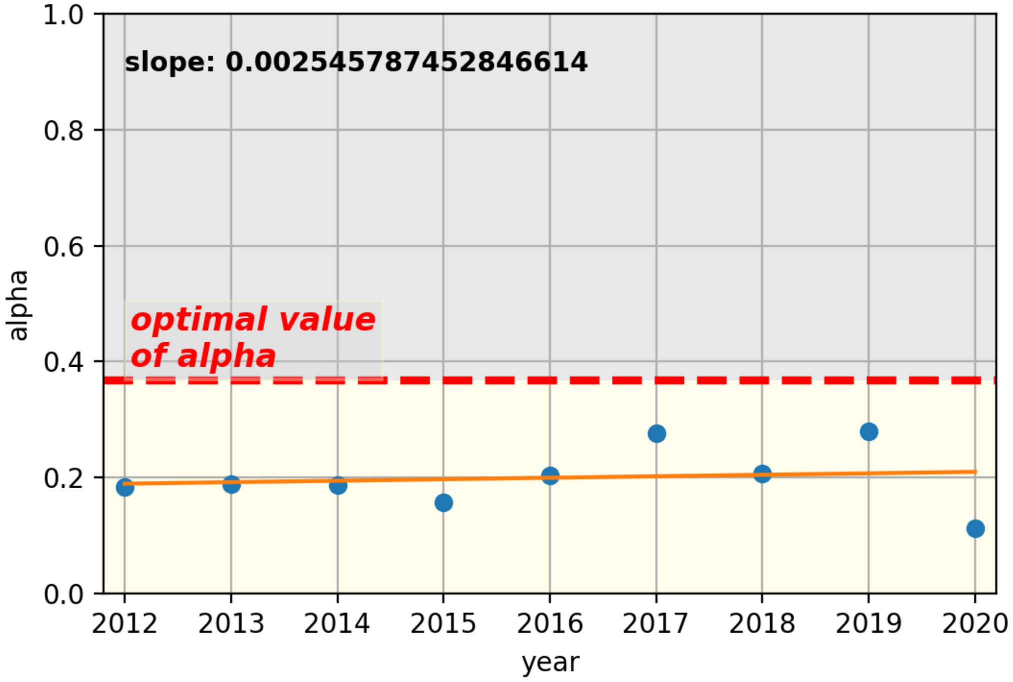

Figure 15: Trendline (HS: 850650)

6.2.2 Cells and Batteries: primary, parts thereof (HS: 850690)

This product's alpha values stay near the optimal alpha value over the nine-year time span. The range of alpha values for this product is 0.114 with 0.412 as the highest value in 2019 and 0.299 as the lowest value in 2015. The trendline over the nine-year period indicates a slope of 0.0073, showing a slight upward trend, higher efficiency of the product, for the product.

Table 13: Alpha Values (HS: 850690)

Alpha	Year
0.373656	2012
0.343613	2013
0.32861	2014
0.298527	2015
0.368879	2016
0.36742	2017
0.376256	2018
0.412147	2019
0.391316	2020

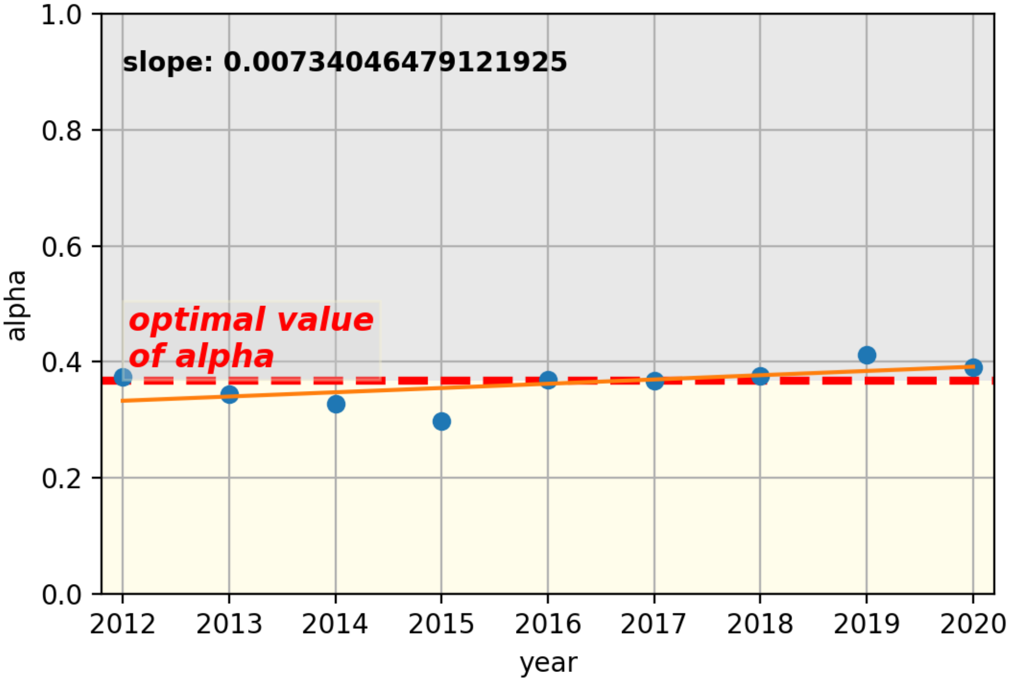

Figure 16: Trendline (HS: 850690)

6.2.3 Electric Vehicles (HS: 870911)

The available 4-years of data shows an overall slope growing towards redundancy. It is to be noted, however, that the 2019 and 2020 data is affected by the COVID-19 pandemic and that makes up half of the available data points.

Table 14: Alpha Values (HS6: 870911)

Alpha	Year
0.367189	2017
0.318311	2018
0.331136	2019
0.342876	2020

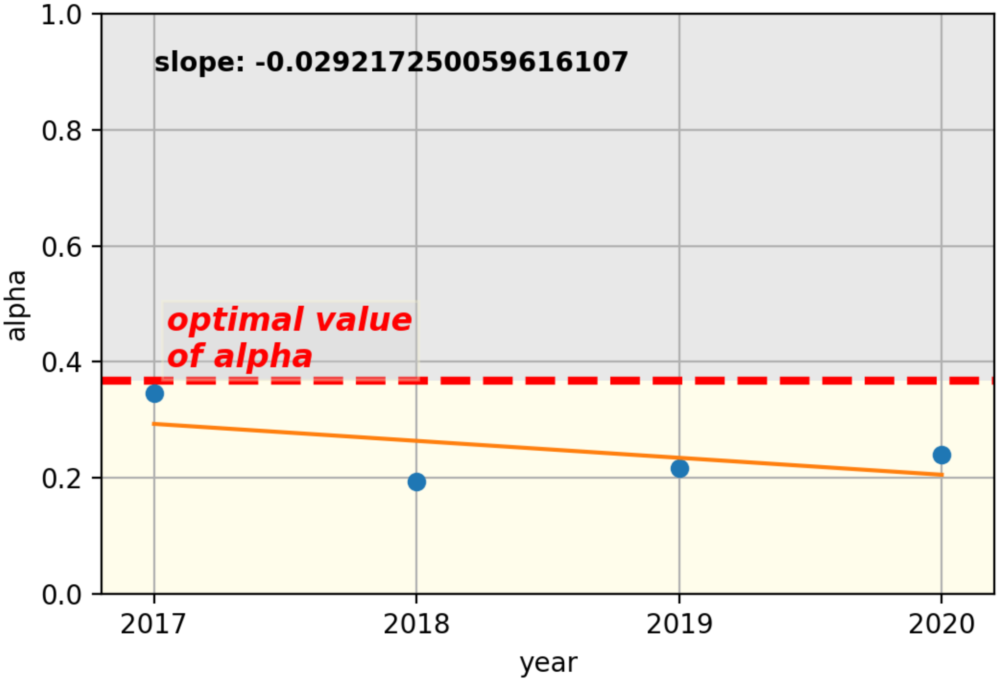

Figure 17: Trendline (HS6: 870911)

Renewable Energy

6.3 Solar Energy

The graphs below, Figure 18Figure 7, show the alpha values over the past nine-years for solar energy products. The products that pertain to solar energy products will be discussed individually.

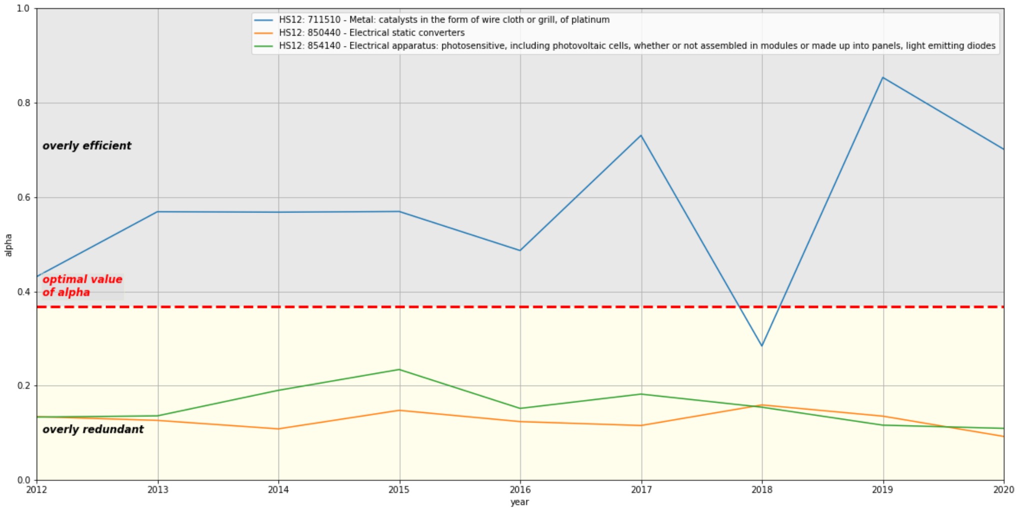

Figure 18: Solar Energy

6.3.1 Metal: catalysts in the form of wire cloth or grill, of platinum (HS6: 711510)

For this product all years, except for 2018 are above the optimal alpha value and are therefore overly efficient. This is shown in the slope value for nine-year trendline of 0.0255, which is positive and growing more efficient every year. The minimum value, or most redundant network year, is 0.284 in 2018. In comparison, the maximum value is the subsequent year, 2019, with an alpha of 0.854.

Table 15: Alpha Values (HS6: 711510)

Alpha	Year
0.431057	2012
0.568936	2013
0.567868	2014
0.569389	2015
0.486553	2016
0.730762	2017
0.283974	2018
0.853658	2019
0.70148	2020

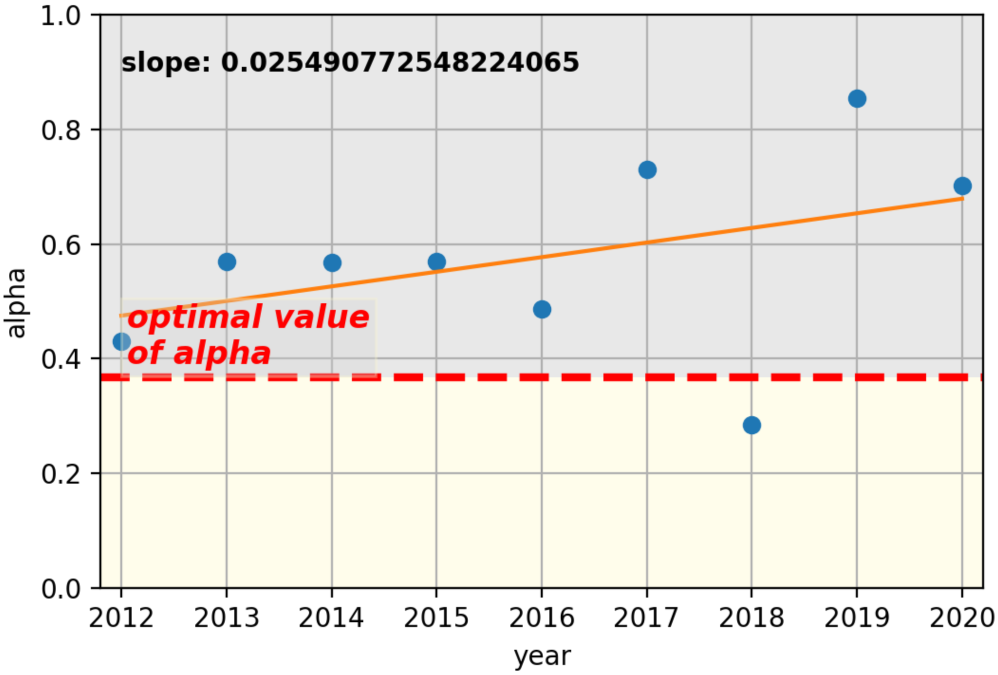

Figure 19: Trendline (HS6: 711510)

6.3.2 Electrical Static Converters (HS6: 850440)

This product's alpha values have remained low overtime, indicating a very redundant system throughout the nine-year timespan, all values are under the optimal alpha value line. The range of the values throughout the timeframe is 0.067, showing that there isn't a high variability between values throughout the nine-year period, this is also shown in the slope of the trendline -0.0012 which shows a relatively flat line.

Table 16: Alpha Values (HS6: 850440)

Alpha	Year
0.134179	2012
0.126281	2013
0.108334	2014
0.147625	2015
0.123738	2016
0.11542	2017
0.159046	2018
0.135324	2019
0.092356	2020

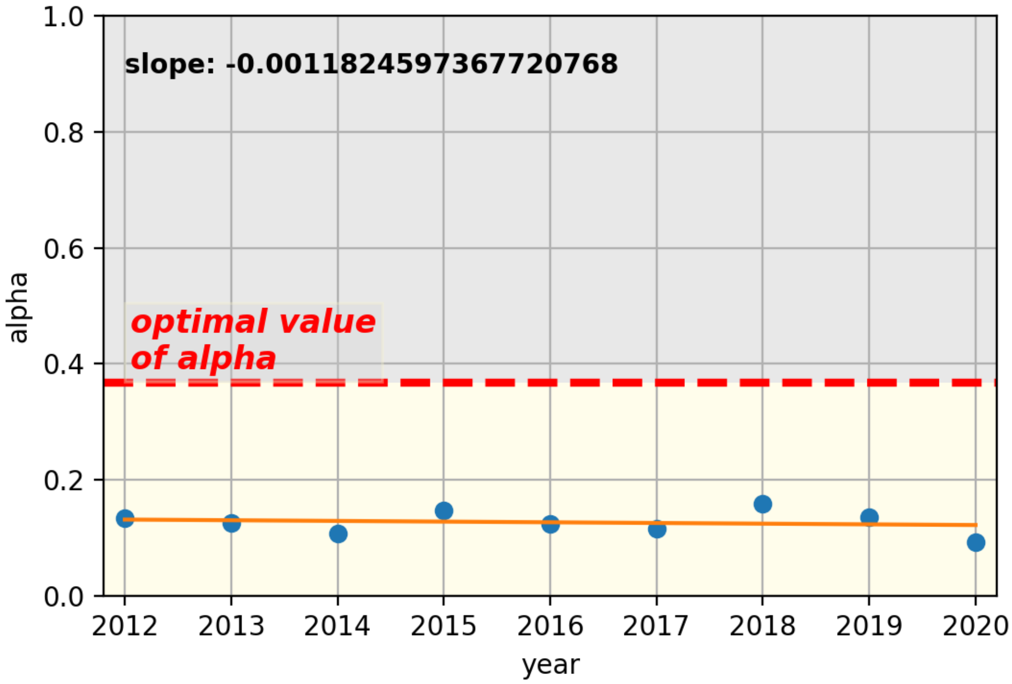

Figure 20: Trendline (HS6: 850440)

6.3.3 Electrical apparatus: photosensitive, including photovoltaic cells, whether or not assembled in modules or made up into panels, light emitting diodes (HS6: 854140)

This product's alpha values have remained under the optimal alpha value line overtime, indicating a redundant system throughout the nine-year timespan. The range of the values is 0.124, with the maximum alpha value occurring in 2015 and minimum in 2020. In this case the slope of the trendline is negative, however relatively flat with a value of -0.0046.

Table 17: Alpha Values (HS6: 854140)

Alpha	Year
0.133311	2012
0.135904	2013
0.190045	2014
0.234229	2015
0.151733	2016
0.182036	2017
0.154281	2018
0.11619	2019
0.10939	2020

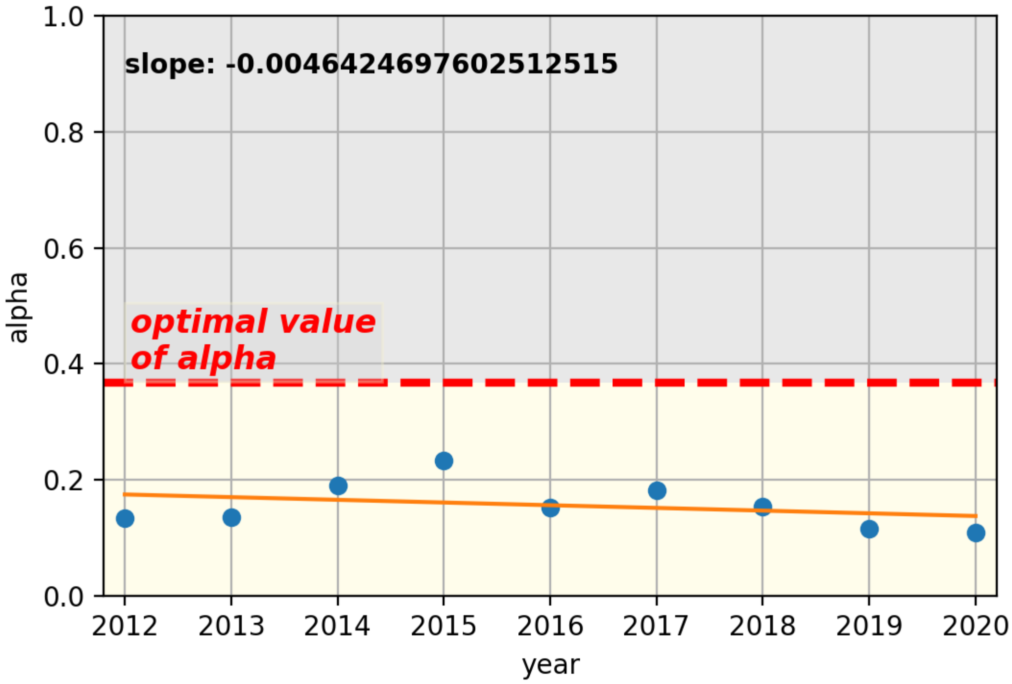

Figure 21: Trendline (HS6: 854140)

6.4 Geothermal Energy

All the products applicable for geothermal energy have a small range between their alpha values over the nine-year period, therefore the slope of all the trendlines are relatively flat. All products besides *Refrigerating or freezing equipment: parts, furniture designed to receive refrigerating or freezing equipment (HS6: 841891)* are well always below the optimal value of alpha making the networks overly redundant, therefore less vulnerable to supply chain disruptions.

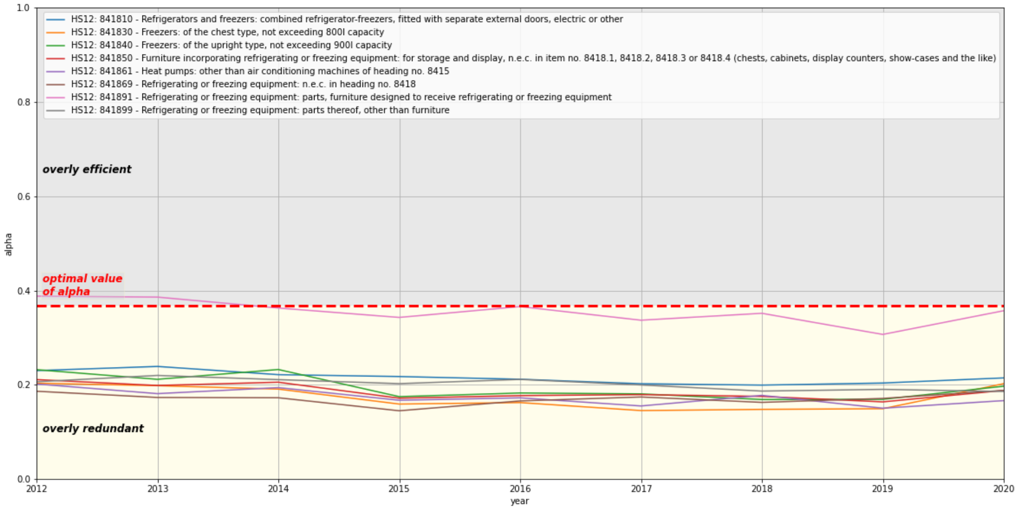

Figure 22: Geothermal Energy

6.4.1 Refrigerators and Freezers: combined refrigerator-freezers, fitted with separate external doors, electric or other (HS6: 841810)

This product's alpha values range between 0.239, in 2013, and 0.199, in 2018, leading to a range of 0.0396 between all alpha values. This leads to a relatively flat trendline with a slope of -0.0037, this system is redundant overtime and based on the trendline if it continues in the same pattern it will continue to remain redundant overtime.

Table 18: Alpha Values (HS6: 841810)

Alpha	Year
0.230041	2012
0.238905	2013
0.221487	2014
0.217478	2015
0.211749	2016
0.202212	2017
0.199291	2018
0.203685	2019
0.214586	2020

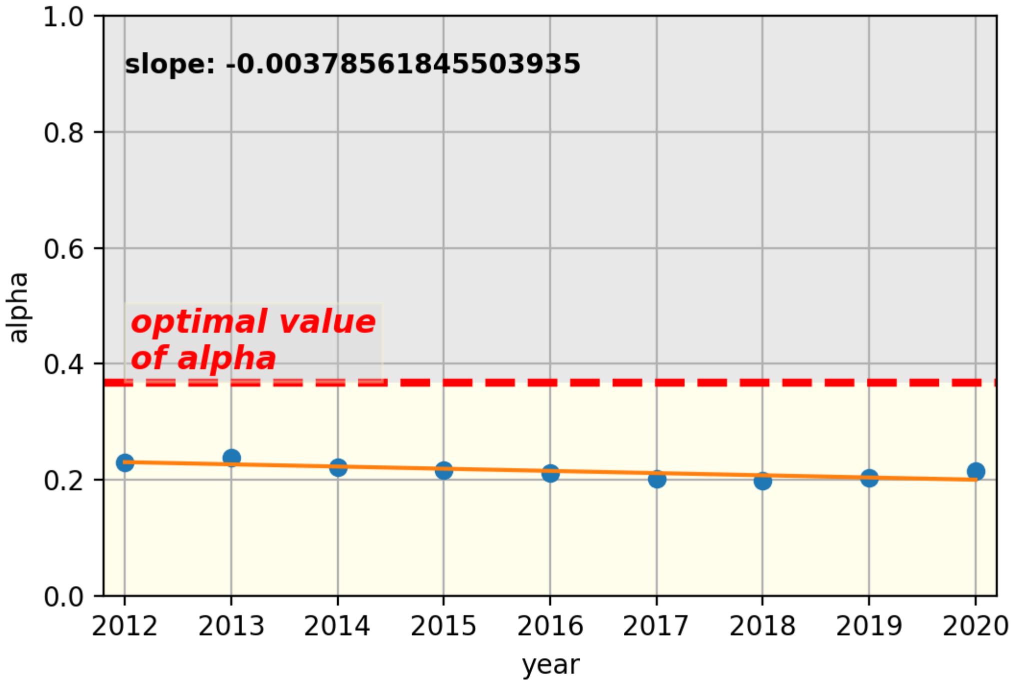

Figure 23: Trendline (HS6: 841810)

6.4.2 Freezers: of the chest type, not exceeding 800L capacity (HS6: 841830)

This product has a maximum alpha value 0.203, in 2012, and a minimum value of 0.145, in 2017, this leads to a range of 0.058 between the alpha values. The trendline based on the data for the alpha values is relatively flat with a slope of -0.0042. This system has stayed overly efficient and is predicted to do so overtime if it follows the trendline.

Table 19: Alpha Values (HS6: 841830)

Alpha	**Year**
0.203313	2012
0.198129	2013
0.190852	2014
0.159088	2015
0.162206	2016
0.14527	2017
0.147764	2018
0.149217	2019
0.202362	2020

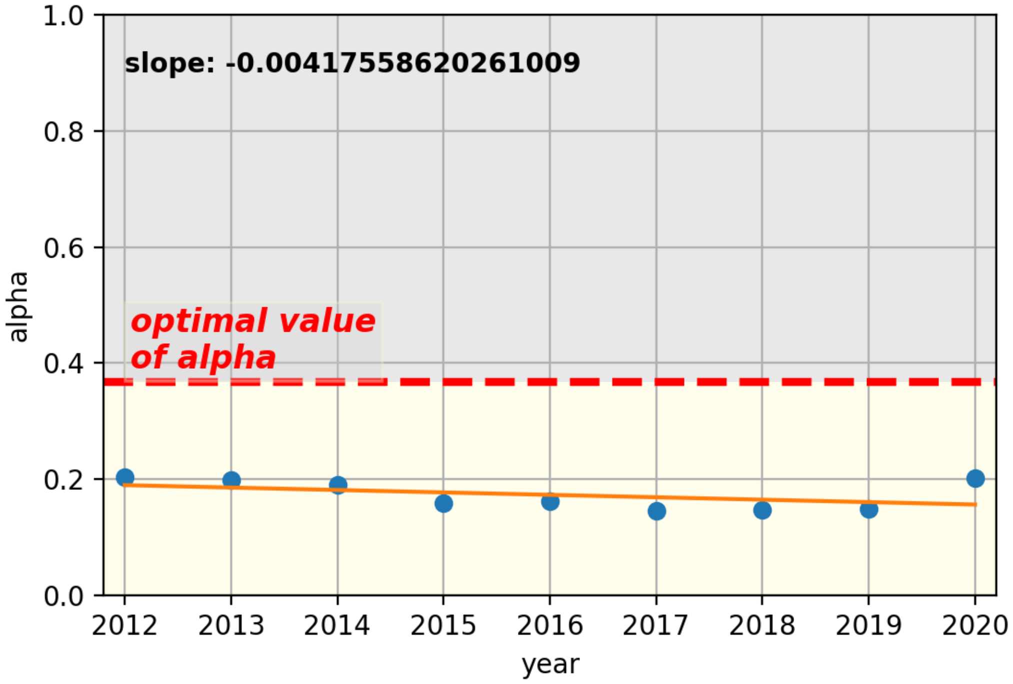

Figure 24: Trendline (HS6: 841830)

6.4.3 Freezers: of the upright type, not exceeding 900L capacity (HS6: 841840)

The product's alpha values range is 0.063 with a maximum value of 0.232, in 2012, and a minimum of 0.169 in 2018. There is an overall flat trendline with a slope of -0.0064, this system is overly redundant throughout the years and is predicted to stay redundant if the future follows the trendline.

Table 20: Alpha Values (HS6: 841840)

Alpha	Year
0.232051	2012
0.211563	2013
0.232421	2014
0.174781	2015
0.182536	2016
0.180702	2017
0.168716	2018
0.169089	2019
0.196932	2020

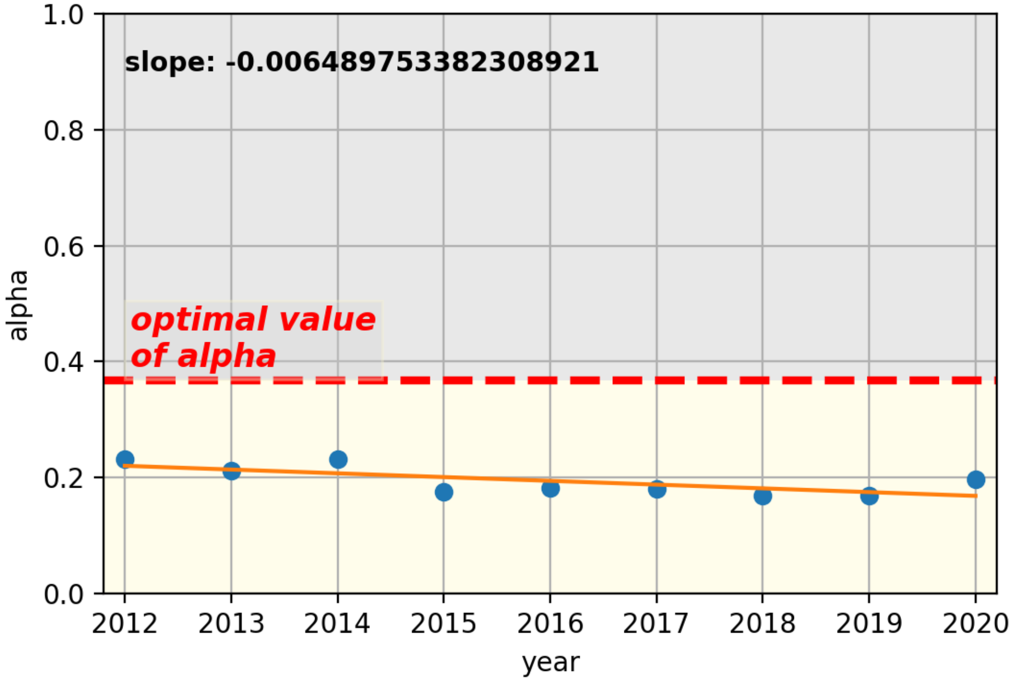

Figure 25: Trendline (HS6: 841840)

6.4.4 Furniture incorporating refrigerating or freezing equipment: for storage and display (HS6: 841850)

This product has a range of 0.047, with a minimum alpha value of 0.163, in 2019, and a maximum value 0.211, in 2012. The slope of the line is -0.0041, leading to a relatively flat line with a slight downward slope, these points are all overly redundant for the nine-year period.

Table 21: Alpha Values (HS6: 841850)

Alpha	Year
0.210938	2012
0.198545	2013
0.205441	2014
0.171551	2015
0.176947	2016
0.179086	2017
0.17536	2018
0.163725	2019
0.18799	2020

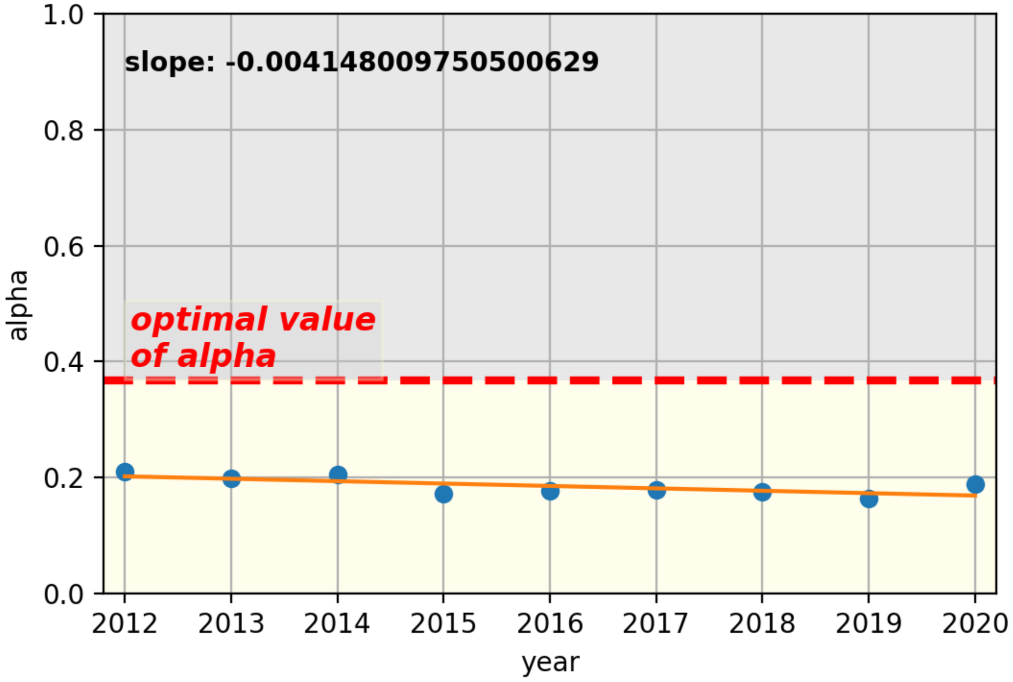

Figure 26: Trendline (HS6: 841850)

6.4.5 Heat pumps: other than air conditioning machines n.e.c. in heading no. 8418 (HS6: 841861)

This product has a range of 0.051, with a minimum alpha value of 0.150, in 2019, and a maximum value 0.201, in 2012. The slope of the line is -0.0046, leading to a relatively flat line with a slight downward slope, these points are all overly redundant for the nine-year period.

Table 22: Alpha Values (HS6: 841861)

Alpha	Year
0.201645	2012
0.181185	2013
0.193969	2014
0.167137	2015
0.17225	2016
0.15503	2017
0.177467	2018
0.150271	2019
0.16638	2020

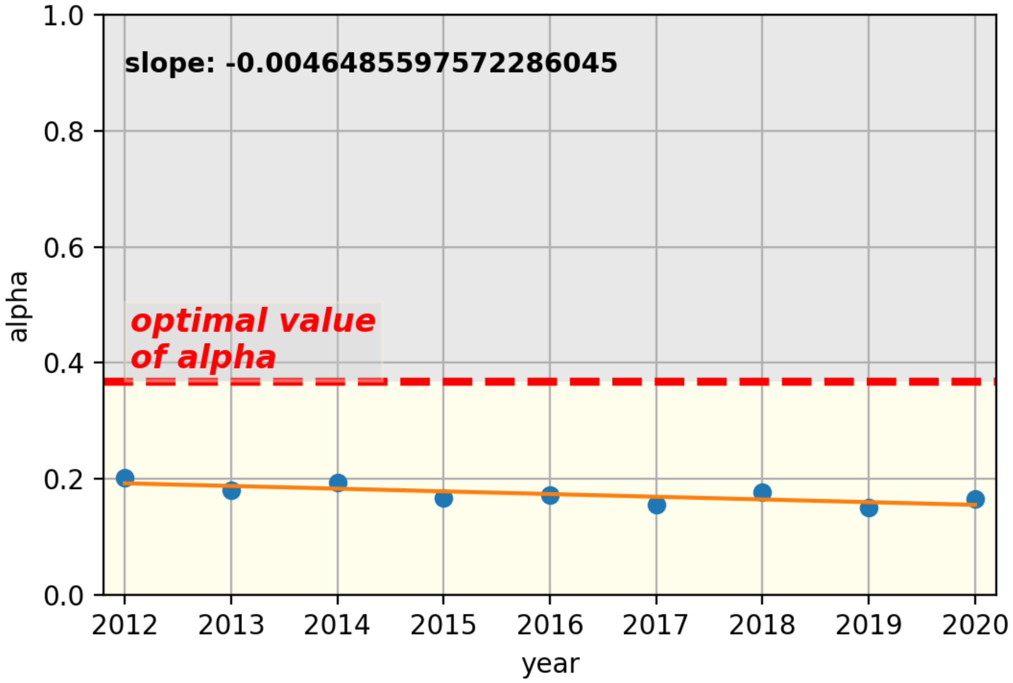

Figure 27: Trendline (HS6: 841861)

6.4.6 Refrigerating or freezing equipment, n.e.c. in heading no. 8418 (HS6: 841869)

This product has a range of 0.043, with a minimum alpha value of 0.145, in 2015, and a maximum value 0.188, in 2020. The slope of the line is -0.0002, leading to a flat line with a slight downward slope, these points are all overly redundant for the nine-year period.

Table 23: Alpha Values (HS6: 841869)

Alpha	Year
0.18625	2012
0.173098	2013
0.172422	2014
0.144843	2015
0.16574	2016
0.174072	2017
0.162655	2018
0.171021	2019
0.188163	2020

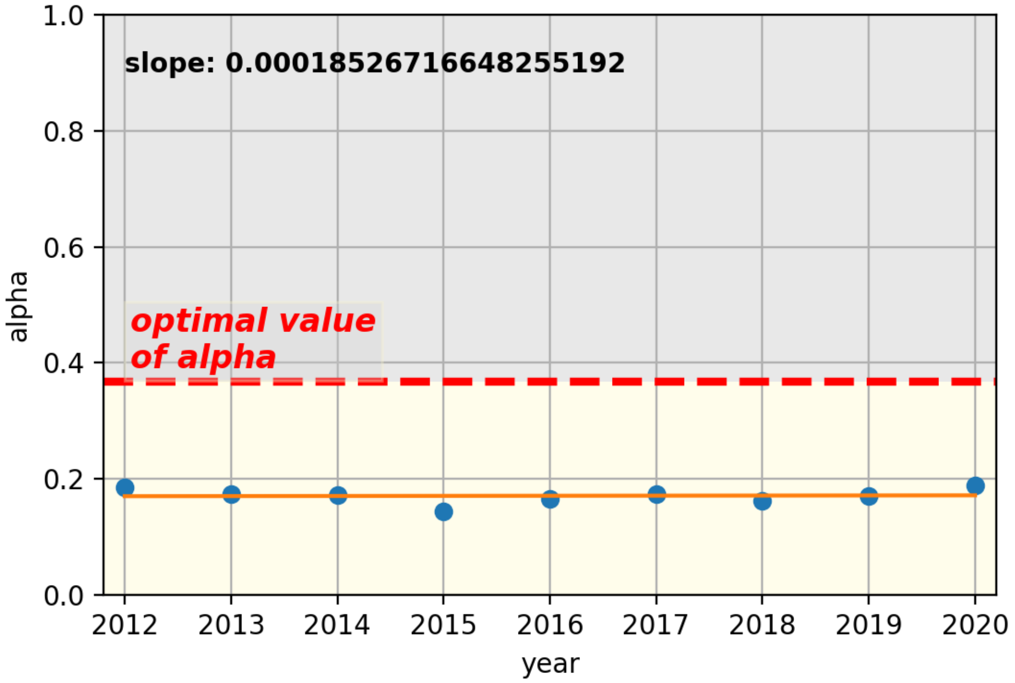

Figure 28: Trendline (HS6: 841869)

6.4.7 Refrigerating or freezing equipment, parts, furniture designed to receive refrigerating or freezing equipment (HS6: 841891)

This product has a range of 0.0812, with a minimum alpha value of 0.307, in 2019, and a maximum value 0.388, in 2012. The slope of the line is -0.0065, leading to a relatively flat line with a slight downward slope, these points are all overly redundant for the nine-year period.

Table 24: Alpha Values (HS6: 841891)

Alpha	Year
0.388141	2012
0.386091	2013
0.362943	2014
0.342957	2015
0.366005	2016
0.337054	2017
0.351718	2018
0.30686	2019
0.357199	2020

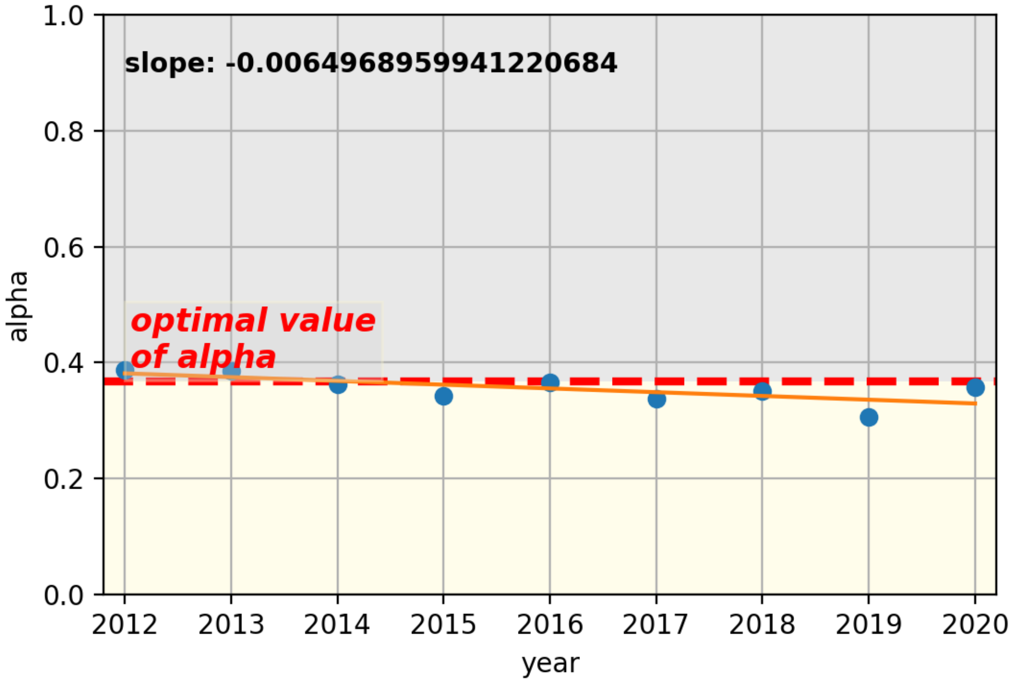

Figure 29: Trendline (HS6: 841891)

6.4.8 Refrigerating or freezing equipment, parts thereof, other than furniture (HS6: 841899)

This product has a range of 0.034, with a minimum alpha value of 0.186, in 2020, and a maximum value 0.219, in 2013. The slope of the line is -0.0037, leading to a relatively flat line with a slight downward slope, these points are all overly redundant for the nine-year period.

Table 25: Alpha Values (HS6: 841899)

Alpha	Year
0.206342	2012
0.219809	2013
0.210901	2014
0.202385	2015
0.211382	2016
0.199613	2017
0.186611	2018
0.190241	2019
0.185801	2020

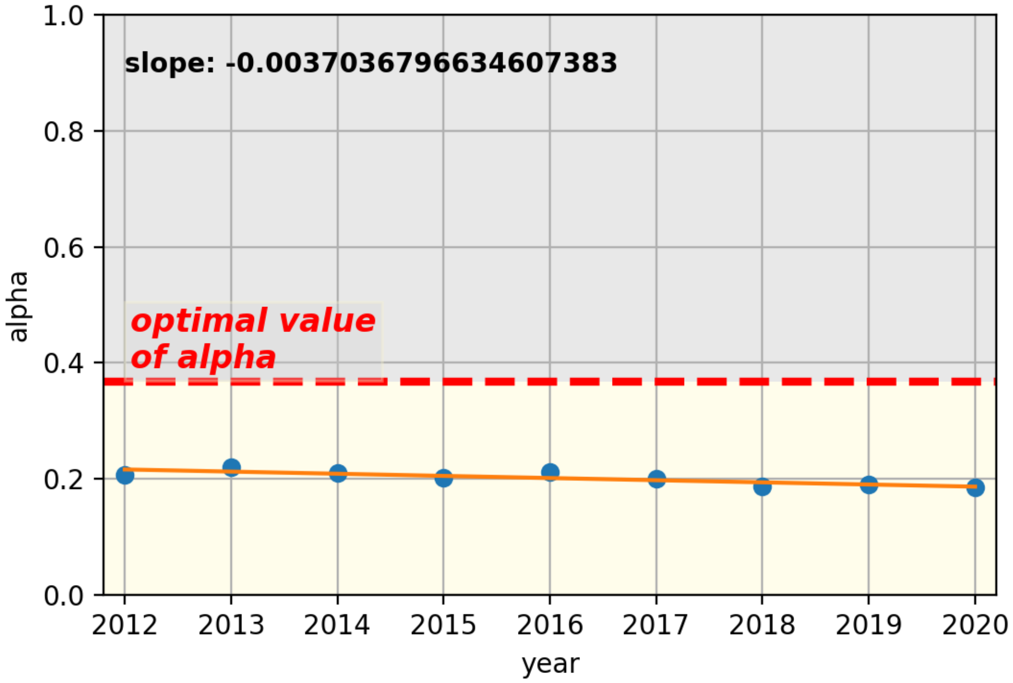

Figure 30: Trendline (HS6: 841899)

6.5 Biomass

The graphs below, Figure 31Figure 18Figure 7, show the alpha values over the past nine-years for solar energy products. The products that pertain to solar energy products will be discussed individually.

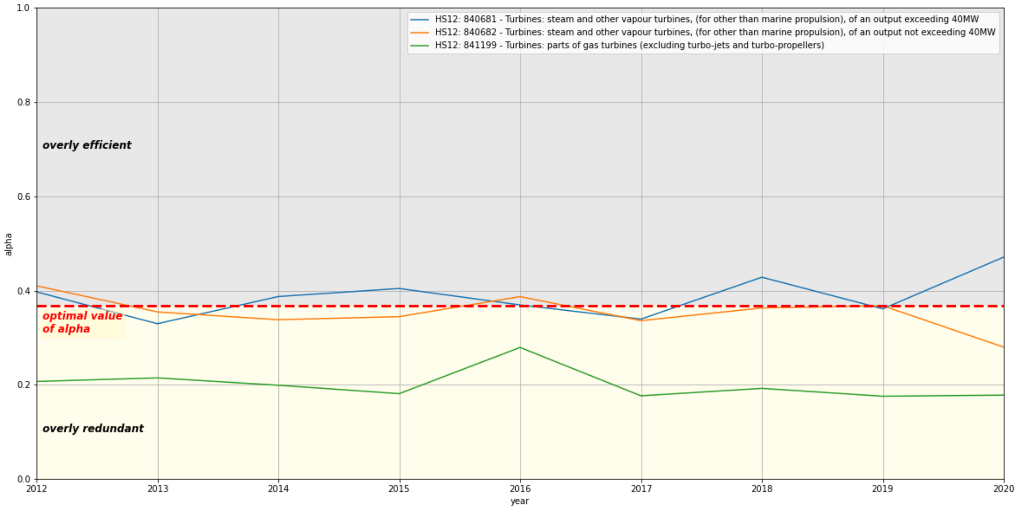

Figure 31: Biomass

6.5.1 Turbines: steam and other vapour turbines (for other than marine propulsion), of an output exceeding 40MW (HS6: 840681)

This product's alpha values hover around the optimal alpha value, with a minimum value of 0.330, in 2013, and a maximum of 0.471, in 2020 – giving a range of 0.141. The values fluctuate throughout the years not leading to a consistency of increase or decrease throughout the years, however, the trendline is relatively flat with a slope of 0.0068, following this trendline into the future one could say the system will become more efficient overtime.

Table 26: Alpha Values (HS6: 840681)

Alpha	Year
0.397254	2012
0.32962	2013
0.387312	2014
0.404383	2015
0.369489	2016
0.3394	2017
0.428347	2018
0.361195	2019
0.470984	2020

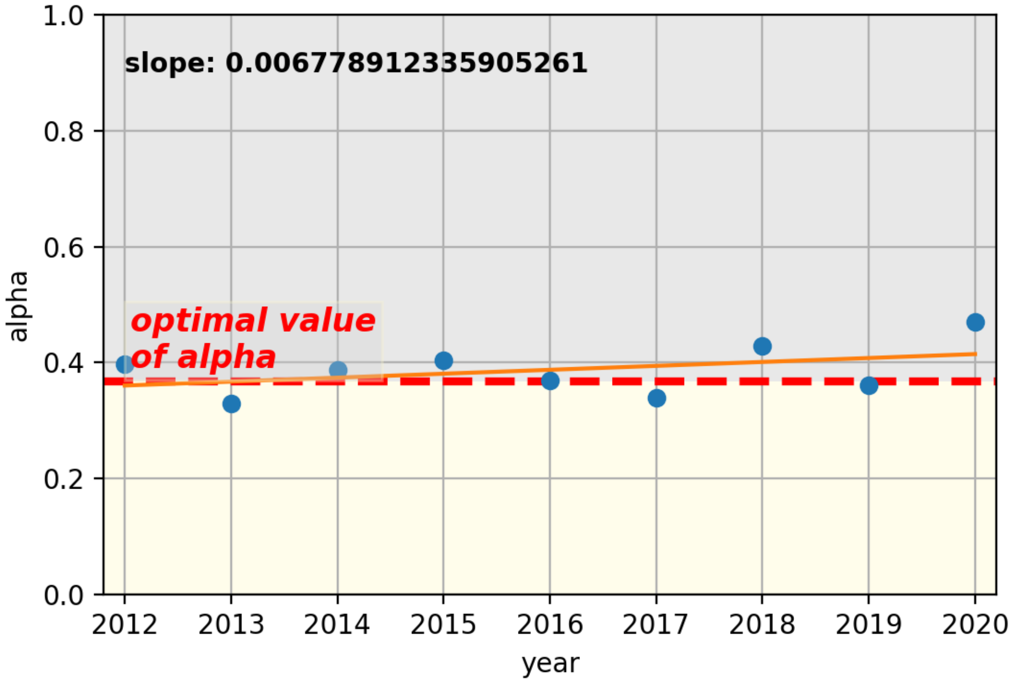

Figure 32: Trendline (HS6: 840681)

6.5.2 Turbines: steam and other vapour turbines (for other than marine propulsion), of an output not exceeding 40MW furniture (HS6: 840682)

This product's alpha values hover around the optimal alpha value, with a maximum of 0.410, in 2012, and a minimum of 0.280, in 2020 – giving a range of 0.130. THe trendline shows a downward turn with a slope of -0,0073, showing an incline towards a redundant system overtime if the trend continues.

Table 27: Alpha Values (HS6: 840682)

Alpha	Year
0.410098	2012
0.35466	2013
0.338101	2014
0.344667	2015
0.38714	2016
0.336062	2017
0.363106	2018
0.367792	2019
0.279901	2020

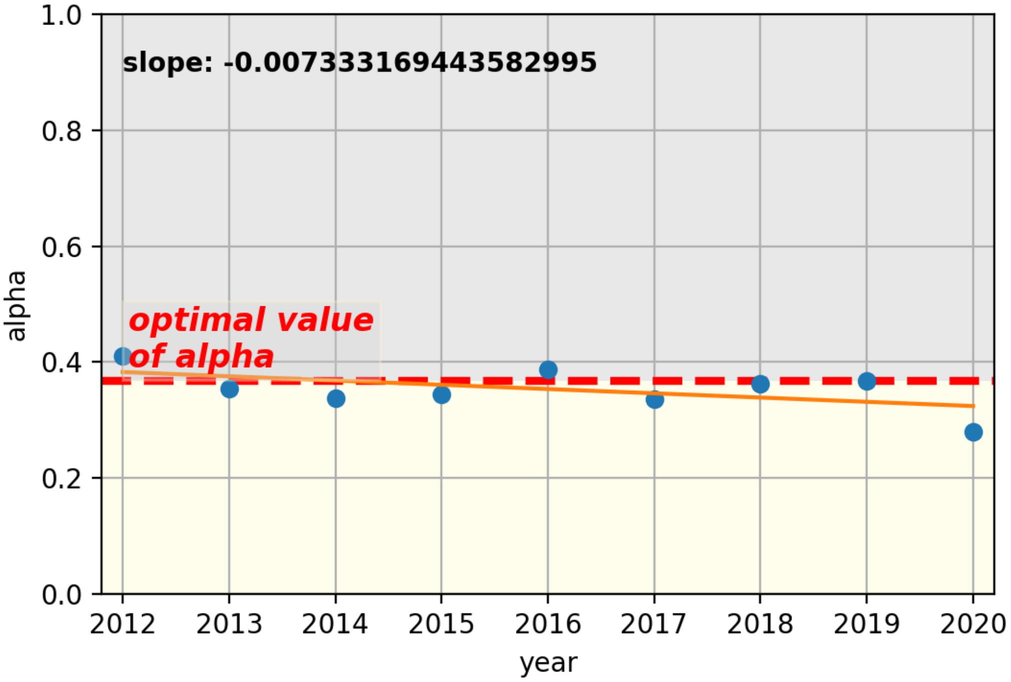

Figure 33: Trendline (HS6: 840682)

6.5.3 Turbines: parts of gas turbines (excluding turbo-jets and turbo-propellers) (HS6: 841199)

This product's alpha values are all below the optimal alpha value indicating a redundant system throughout. The maximum value over the nine-year span is in 2016, with a value of 0.279, and a minimum in 2019, with a value of 0.176. The range of values for this product is 0.103. The trendline for this product is downturned with a slope of -0.0042 meaning the system is becoming slightly more redundant over time and is predicted to do so based on the trendline.

Table 28: Alpha Values (HS6: 841199)

Alpha	Year
0.207036	2012
0.2146	2013
0.198969	2014
0.18113	2015
0.279214	2016
0.176586	2017
0.192349	2018
0.175672	2019
0.178003	2020

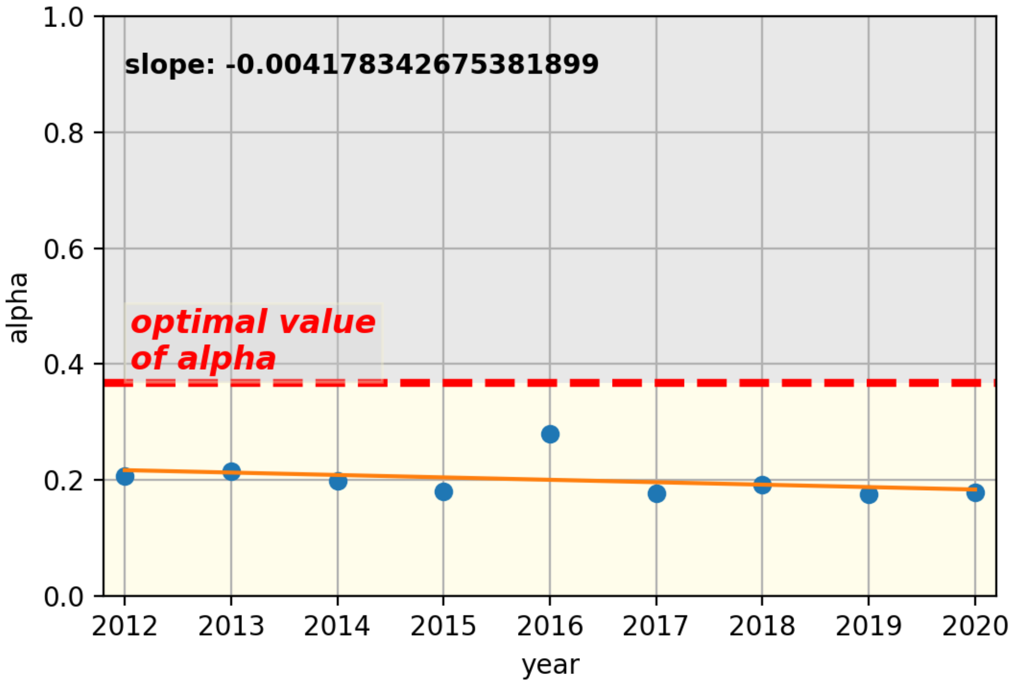

Figure 34: Trendline (HS6: 841199)

Appendix B: Network Analysis

Network graphs can be found here: https://share.streamlit.io/pattanyj/thesis/main/cobalt_prod_app.py

HS6: 711510, 282739, and 840681

6.6 Metal: catalysts in the form of wire cloth or grill, of platinum (HS6: 711510)

6.6.1 2012-2014 Information

Table 29: Top 10 importers 2012-2014 (HS6: 711510)

Country	**Imports (tons)**
Germany	655.034
France, Monaco	211.226
Belgium	168.975
United Kingdom	131.264
Italy	93.869
United Arab Emirates	80.866
Denmark	67.99
Austria	27.964
Slovakia	19.964
Netherlands	14.966

Table 30: Top 10 Exporters 2012-2014 (HS6: 711510)

Country	**Exports (tons)**
Denmark	314.803
Czechia	287.347
Netherlands	218.178
United Kingdom	178.475
Bulgaria	164.812
Spain	97.719
France, Monaco	90.113
Sweden	41.146
Germany	39.207
China	31.915

Table 31: Top 10 countries with highest betweenness centrality 2012-2014 (HS6: 711510)

Country	**Betweenness Centrality**
Germany	0.188922
United Kingdom	0.134612
South Africa	0.069175
USA, Puerto Rico and US Virgin Islands	0.060505
Italy	0.039156
Denmark	0.035231
United Arab Emirates	0.031947
China	0.02559
Republic of Korea	0.022791
Netherlands	0.022473

6.6.2 2015-2017 Information

Table 32: Top 10 importers 2015-2017 (HS6: 711510)

Country	Imports (tons)
Slovakia	2348.424
France, Monaco	1068.186
Germany	630.21
Ireland	317.058
Bulgaria	209.889
United Kingdom	180.466
Belgium	134.831
Netherlands	89.834
Lithuania	79.721
Czechia	63.785

Table 33: Top 10 exporters 2015-2017 (HS6: 711510)

Country	Exports (tons)
United Kingdom	3761.04
Czechia	289.277
Denmark	225.661
Greece	205.494
Bulgaria	200.885
United Arab Emirates	122.251
South Africa	73.836
Spain	69.186
China	67.305
Estonia	51.049

Table 34: Top 10 countries with highest betweenness centrality 2015-2017 (HS6: 711510)

Country	Betweenness Centrality
Germany	0.160728
United Kingdom	0.150697
South Africa	0.077064
USA, Puerto Rico and US Virgin Islands	0.069915
Netherlands	0.063485
China	0.0523
Australia	0.023652
United Arab Emirates	0.020994
India	0.020704
Italy	0.018258

6.6.3 2018-2020 Information

Table 35: Top 10 importers 2018-2020 (HS6: 711510)

Country	Imports (tons)
Indonesia	1007.249
Republic of Korea	320.744
Germany	185.156
United Kingdom	178.837
Bulgaria	84.717
Portugal	55.637
France, Monaco	51.655
Denmark	32.559
Czechia	28.164
Belgium	19.578

Table 36: Top 10 exporters 2018-2020 (HS6: 711510)

Country	Exports (tons)
China	1007.371
Australia	323.603
Bulgaria	202.639
Denmark	127.345
Greece	91.604
South Africa	47.438
Italy	40.599
Spain	34.237
Germany	26.074
Lithuania	23.152

Table 37: Top 10 countries with highest betweenness centrality 2018-2020 (HS6: 711510)

Country	Betweenness Centrality
Germany	0.177599
United Kingdom	0.129265
USA, Puerto Rico and US Virgin Islands	0.069284
India	0.042761
South Africa	0.039899
Denmark	0.024664
France, Monaco	0.024255
China	0.021146
Bulgaria	0.017312
Japan	0.016959

6.7 Cobalt chlorides (2007-2500) (HS6: 282739)

6.7.1 2012-2014 Information

Table 38: Top 10 importers 2012-2014 (HS6: 282739)

Country	Imports (tons)
Netherlands	230057.4
France, Monaco	154686
Belgium	135144.4
Switzerland, Liechtenstein	126243.4
Germany	124308.1
Saudi Arabia	84414.63
Italy	79561.02
Denmark	77987.61
China, Hong Kong Special Administrative Region	77347.02
Austria	58670.94

Table 39: Top 10 Exporters 2012-2014 (HS6: 282739)

Country	Exports (tons)
Germany	378964.9
China	291158
Belgium	211976.6
France, Monaco	112407
Jordan	105969.9
India	93169.16
Austria	82466.97
Sweden	82237.74
Spain	66233.12
USA, Puerto Rico and US Virgin Islands	53164.02

Table 40: Top 10 countries with highest betweenness centrality 2012-2014 (HS6: 282739)

Country	Betweenness Centrality
Germany	0.077845
USA, Puerto Rico and US Virgin Islands	0.073557
France, Monaco	0.051582
China	0.043424
India	0.033366
Netherlands	0.027506
United Arab Emirates	0.025154
South Africa	0.024285
Russian Federation	0.023394
Belgium	0.019956

6.7.2 2015-2017 Information

Table 41: Top 10 importers 2015-2017 (HS6: 282739)

Country	**Imports (tons)**
Netherlands	229211.8
France, Monaco	187413
Belgium	180154.2
Germany	125489.5
Switzerland, Liechtenstein	123134.3
Italy	97172.71
India	84399.78
China, Hong Kong Special Administrative Region	83055.14
United Kingdom	74240.04
Japan	71822.93

Table 42: Top 10 exporters 2015-2017 (HS6: 282739)

Country	**Exports (tons)**
Germany	455227.3
China	304442.4
Belgium	225399.7
France, Monaco	111592.9
Austria	103485.7
Hungary	82361.85
India	78604.26
Spain	66165.76
Jordan	62484.33
Finland	62189.86

Table 43: Top 10 countries with highest betweenness centrality 2015-2017 (HS6: 282739)

Country	**Betweenness Centrality**
Netherlands	0.2108
USA, Puerto Rico and US Virgin Islands	0.078241
India	0.056267
Germany	0.048688
China	0.026861
Spain	0.025161
France, Monaco	0.024909
Belgium	0.02305
Austria	0.017639
Russian Federation	0.017584

6.7.3 2018-2020 Information

Table 44: Top 10 importers 2018-2020 (HS6: 282739)

Country	Imports (tons)
Netherlands	227584.2
France, Monaco	197464.7
Belgium	197118
Germany	192444.4
India	174078
Switzerland, Liechtenstein	120060.1
United Kingdom	105948.9
China, Hong Kong Special Administrative Region	105472.8
Italy	103419.5
USA, Puerto Rico and US Virgin Islands	97913.23

Table 45: Top 10 exporters 2018-2020 (HS6: 282739)

Country	Exports (tons)
Germany	468691.2
China	355495.8
Belgium	265149.7
India	176890
Austria	168507.6
Jordan	125980.1
France, Monaco	113897.1
Spain	105668.5
Sweden	104641.3
Hungary	78561.43

Table 46: Top 10 countries with highest betweenness centrality 2018-2020 (HS6: 282739)

Country	Betweenness Centrality
USA, Puerto Rico and US Virgin Islands	0.071751
India	0.065663
Netherlands	0.045922
Germany	0.040332
France, Monaco	0.031103
South Africa	0.028595
China	0.025967
Spain	0.020569
Belgium	0.019317
Israel	0.018171

6.8 Turbines: steam and other vapour turbines, (for other than marine propulsion), of an output exceeding 40MW (HS6: 840681)

6.8.1 2012-2014 Information

Table 47: Top 10 importers 2012-2014 (HS6: 840681)

Country	**Imports (tons)**
South Africa	147563.5
Brazil	59080.94
Indonesia	19531.86
Turkey	18663.62
Guatemala	10180.11
Republic of Korea	8927.727
India	5188.609
Viet Nam	5161.663
USA, Puerto Rico and US Virgin Islands	5150.129
China	3951.544

Table 48: Top 10 Exporters 2012-2014 (HS6: 840681)

Country	**Exports (tons)**
China	105814
Poland	50145.52
Germany	43131.39
USA, Puerto Rico and US Virgin Islands	28650.8
Japan	23267.01
Israel	16957.21
Thailand	13326.34
Czechia	11872.85
Sweden	10793.17
Austria	8410.601

Table 49: Top 10 countries with highest betweenness centrality 2012-2014 (HS6: 840681)

Country	**Betweenness Centrality**
USA, Puerto Rico and US Virgin Islands	0.137894
South Africa	0.137637
China	0.073492
Germany	0.071013
France, Monaco	0.058534
Italy	0.055628
United Kingdom	0.052278
Dominican Republic	0.044171
Guatemala	0.029816
Saudi Arabia	0.025769

6.8.2 2015-2017 Information

Table 50: Top 10 importers 2015-2017 (HS6: 840681)

Country	Imports (tons)
South Africa	478398.2
Turkey	22316.08
Viet Nam	5469.803
Indonesia	4565.232
Philippines	3835.321
Bangladesh	3560.191
Plurinational State of Bolivia	3186.894
China	2888.367
Other Asia, not elsewhere specified	2758.162
USA, Puerto Rico and US Virgin Islands	2701.141

Table 51: Top 10 exporters 2015-2017 (HS6: 840681)

Country	Exports (tons)
Netherlands	397189.9
Germany	63724.19
China	30579.74
Poland	24989.07
Japan	14650.91
United Kingdom	4668.243
Czechia	3985.668
USA, Puerto Rico and US Virgin Islands	3742.264
Belgium	3475.337
Russian Federation	2937.783

Table 52: Top 10 countries with highest betweenness centrality 2015-2017 (HS6: 840681)

Country	Betweenness Centrality
South Africa	0.098728
USA, Puerto Rico and US Virgin Islands	0.0906
Germany	0.069641
France, Monaco	0.069515
China	0.049219
Italy	0.04101
United Kingdom	0.039385
Netherlands	0.032534
Turkey	0.023451
Switzerland, Liechtenstein	0.019894

6.8.3 2018-2020 Information

Table 53: Top 10 importers 2018-2020 (HS6: 840681)

Country	Imports (tons)
South Africa	27635.33
Turkey	26227.81
Indonesia	19097.3
Plurinational State of Bolivia	18459.49
China	18112.48
Pakistan	4809.897
India	3324.227
Japan	2750.321
USA, Puerto Rico and US Virgin Islands	2490.783
Viet Nam	2480.948

Table 54: Top 10 exporters 2018-2020 (HS6: 840681)

Country	Exports (tons)
China	45471.78
India	25748.22
Germany	22470.04
Japan	16253.19
Pakistan	13097.96
Czechia	4126.104
Poland	3806.49
Netherlands	2906.774
United Kingdom	2654.475
Brazil	2114.338

Table 55: Top 10 countries with highest betweenness centrality 2018-2020 (HS6: 840681)

Country	Betweenness Centrality
USA, Puerto Rico and US Virgin Islands	0.12507
Germany	0.0751
China	0.059533
France, Monaco	0.048423
South Africa	0.038372
United Kingdom	0.028454
Singapore	0.027908
Italy	0.027417
India	0.024362
Japan	0.021796

Appendix C: World Governance Index

Table 56: Average World Governance Index Value for Countries, Calculated using data from Source: https://info.worldbank.org/governance/wgi/

Country/Territory	Code	WGI Index Average
Aruba	ABW	1.18
Andorra	ADO	1.37
Afghanistan	AFG	-1.65
Angola	AGO	-1.14
Anguilla	AIA	1.13
Albania	ALB	-0.26
Netherlands Antilles (former)	ANT	0.82
United Arab Emirates	ARE	0.55
Argentina	ARG	-0.19
Armenia	ARM	-0.28
American Samoa	ASM	0.78
Antigua and Barbuda	ATG	0.67
Australia	AUS	1.58
Austria	AUT	1.55
Azerbaijan	AZE	-0.83
Burundi	BDI	-1.28
Belgium	BEL	1.31
Benin	BEN	-0.23
Burkina Faso	BFA	-0.38
Bangladesh	BGD	-0.86
Bulgaria	BGR	0.18
Bahrain	BHR	0.05
Bahamas, The	BHS	0.95
Bosnia and Herzegovina	BIH	-0.38
Belarus	BLR	-0.79
Belize	BLZ	-0.06
Bermuda	BMU	1.1
Bolivia	BOL	-0.52
Brazil	BRA	-0.03
Barbados	BRB	1.12
Brunei Darussalam	BRN	0.57

Bhutan	BTN	0.26
South Sudan	SSD	-1.84
Botswana	BWA	0.69
Central African Republic	CAF	-1.39
Canada	CAN	1.62
Switzerland	CHE	1.75
Chile	CHL	1.12
China	CHN	-0.49
Côte d'Ivoire	CIV	-0.9
Cameroon	CMR	-0.96
Congo, Rep.	COG	-1.12
Cook Islands	COK	0.04
Colombia	COL	-0.38
Comoros	COM	-0.91
Cape Verde	CPV	0.51
Costa Rica	CRI	0.62
Cuba	CUB	-0.58
Cayman Islands	CYM	1.08
Cyprus	CYP	0.98
Czech Republic	CZE	0.9
Germany	DEU	1.49
Djibouti	DJI	-0.76
Dominica	DMA	0.66
Denmark	DNK	1.78
Dominican Republic	DOM	-0.3
Algeria	DZA	-0.87
Ecuador	ECU	-0.63
Egypt, Arab Rep.	EGY	-0.66
Eritrea	ERI	-1.29
Spain	ESP	0.95
Estonia	EST	1.07
Ethiopia	ETH	-0.94
Finland	FIN	1.84
Fiji	FJI	-0.13
France	FRA	1.19
Micronesia, Fed. Sts.	FSM	0.19
Gabon	GAB	-0.54
United Kingdom	GBR	1.46

Georgia	GEO	-0.12
Ghana	GHA	0
Guinea	GIN	-1.1
Gambia, The	GMB	-0.47
Guinea-Bissau	GNB	-1.1
Equatorial Guinea	GNQ	-1.29
Greece	GRC	0.5
Grenada	GRD	0.43
Greenland	GRL	1.39
Guatemala	GTM	-0.6
French Guiana	GUF	0.88
Guam	GUM	0.72
Guyana	GUY	-0.3
Hong Kong SAR, China	HKG	1.35
Honduras	HND	-0.6
Croatia	HRV	0.34
Haiti	HTI	-1.19
Hungary	HUN	0.75
Indonesia	IDN	-0.49
India	IND	-0.23
Ireland	IRL	1.48
Iran, Islamic Rep.	IRN	-0.98
Iraq	IRQ	-1.57
Iceland	ISL	1.61
Israel	ISR	0.63
Italy	ITA	0.63
Jamaica	JAM	0.08
Jordan	JOR	-0.04
Japan	JPN	1.23
Kazakhstan	KAZ	-0.56
Kenya	KEN	-0.67
Kyrgyz Republic	KGZ	-0.77
Cambodia	KHM	-0.81
Kiribati	KIR	0.15
St. Kitts and Nevis	KNA	0.67
Korea, Rep.	KOR	0.75
Kuwait	KWT	0.09
Lao PDR	LAO	-0.91

Lebanon	LBN	-0.65
Liberia	LBR	-1.05
Libya	LBY	-1.35
St. Lucia	LCA	0.7
Liechtenstein	LIE	1.54
Sri Lanka	LKA	-0.27
Lesotho	LSO	-0.19
Lithuania	LTU	0.78
Luxembourg	LUX	1.71
Latvia	LVA	0.67
Kosovo	KSV	-0.39
Macao SAR, China	MAC	0.78
Morocco	MAR	-0.27
Monaco	MCO	0.98
Moldova	MDA	-0.37
Madagascar	MDG	-0.52
Maldives	MDV	-0.18
Mexico	MEX	-0.17
Marshall Islands	MHL	-0.09
North Macedonia	MKD	-0.19
Mali	MLI	-0.54
Malta	MLT	1.12
Myanmar	MMR	-1.42
Mongolia	MNG	-0.04
Montenegro	MNE	0.05
Mozambique	MOZ	-0.47
Mauritania	MRT	-0.64
Martinique	MTQ	0.85
Mauritius	MUS	0.76
Malawi	MWI	-0.38
Malaysia	MYS	0.36
Namibia	NAM	0.32
Niger	NER	-0.66
Nigeria	NGA	-1.11
Nicaragua	NIC	-0.58
Niue	NIU	-0.24
Netherlands	NLD	1.69
Norway	NOR	1.73

Nepal	NPL	-0.74
Nauru	NRU	0.18
New Zealand	NZL	1.78
Oman	OMN	0.24
Pakistan	PAK	-0.99
Panama	PAN	0.12
Palau	PLW	0.39
Peru	PER	-0.25
Philippines	PHL	-0.37
Papua New Guinea	PNG	-0.61
Poland	POL	0.71
Puerto Rico	PRI	0.67
Korea, Dem. Rep.	PRK	-1.54
Portugal	PRT	1.09
Paraguay	PRY	-0.65
Qatar	QAT	0.44
Réunion	REU	0.9
Romania	ROM	0.11
Russian Federation	RUS	-0.71
Rwanda	RWA	-0.47
Samoa	WSM	0.5
Saudi Arabia	SAU	-0.33
Sudan	SDN	-1.55
Senegal	SEN	-0.16
Singapore	SGP	1.52
Solomon Islands	SLB	-0.39
Sierra Leone	SLE	-0.81
El Salvador	SLV	-0.21
San Marino	SMR	1.06
Somalia	SOM	-2.15
São Tomé and Principe	STP	-0.23
Suriname	SUR	-0.08
Slovak Republic	SVK	0.7
Slovenia	SVN	0.97
Sweden	SWE	1.73
Eswatini	SWZ	-0.6
Seychelles	SYC	0.25
Syrian Arab Republic	SYR	-1.31

Chad	TCD	-1.3
Togo	TGO	-0.85
Thailand	THA	-0.14
Tajikistan	TJK	-1.19
Turkmenistan	TKM	-1.35
Timor-Leste	TMP	-0.66
Tonga	TON	-0.06
Trinidad and Tobago	TTO	0.21
Tunisia	TUN	-0.16
Turkey	TUR	-0.2
Tuvalu	TUV	0.31
Taiwan, China	TWN	0.95
Tanzania	TZA	-0.45
Uganda	UGA	-0.62
Ukraine	UKR	-0.62
Uruguay	URY	0.79
United States	USA	1.28
Uzbekistan	UZB	-1.25
St. Vincent and the Grenadines	VCT	0.69
Venezuela, RB	VEN	-1.22
Virgin Islands (U.S.)	VIR	0.84
Vietnam	VNM	-0.48
Vanuatu	VUT	0.16
West Bank and Gaza	WBG	-0.74
Jersey, Channel Islands	JEY	1.31
Yemen, Rep.	YEM	-1.35
Serbia	SRB	-0.32
South Africa	ZAF	0.29
Congo, Dem. Rep.	ZAR	-1.65
Zambia	ZMB	-0.37
Zimbabwe	ZWE	-1.31