Nijmegen School of Management
Department of Economics and Business Economics
Master's Thesis Economics (MAN-MTHEC)

The "Dark Side" of Decarbonizing the Transport Sector

By Emma Atkins (s1041066)

Nijmegen, 30 June 2024

Program: Master's Program in Economics
Specialisation: International Political Economy
Supervisor: O. Kyrychenko

Radboud Universiteit

Abstract: The Paris Agreement, implemented in 2016, sparked a global push towards decarbonizing the transport sector. In response, the Global North has established policies targeted at the adoption of lithium-ion battery-powered electric vehicles (EVs). Leading to the expansion of lithium mining operations, in order to meet the unprecedented demand for lithium-ion batteries. This quasi-experimental study pioneers the exploration and quantification of the effects of lithium mining on the release of CO2 and PM2.5 emissions, in the lithium mining regions of Argentina, Australia, Chile, and China. The results obtained, robust to a series of placebo tests, indicate that in anticipation of the implementation of the Paris Agreement, CO2 emissions in Western Australia and Antofagasta (Chile) increased by a total of 284.7 and 12,924 metric tonnes, respectively, relative to a synthetic control unit, while PM2.5 emissions remained relatively unchanged. Furthermore, the results indicate that hard-rock lithium mining, despite its more visually impactful nature, is less carbon-intensive per unit of lithium produced, compared to lithium brine mining. In general, the results obtained highlight that policy targeted at decarbonizing the transport sector may understate the carbon intensity of mining the materials required to do so, and therefore overstate the "clean" nature of this transition.

Table of Contents

I. Introduction

Increased greenhouse gas (GHG) emissions have long been acknowledged as the driving force of climate change (Jackson, n.d.). The escalation of climate change impacts has called for an increase in global efforts to reduce these emissions, with an aim to limit the rise in global temperatures to 1.5°C above pre-industrial levels. A notable example of such efforts is the implementation of an international treaty, known as "The Paris Agreement", implemented in 2016 (Horowitz, 2016). Although the Paris Agreement is based on nationally determined commitments, a key area within these voluntary pledges has involved significant efforts to reduce transport emissions, which account for about one-fifth of global GHG emissions (McKay, 2023). These efforts have led to subordinate policies, which promote the adoption of electric vehicles (EVs), such as the European Green Deal (Latief, 2022). As a result, the demand for lithium minerals, required for the production of lithium-ion battery-powered EVs has skyrocketed, leading to the necessary expansion of lithium mining operations (Ciftci & Lemaire, 2023).

Lithium mining primarily takes on two different forms. Lithium brine mining, which makes use of an evaporation process, is primarily employed in the South American Lithium Triangle, which spans the borders of Argentina, Bolivia, and Chile (Berg & Sady-Kennedy, 2021). In contrast, hard-rock, traditional open-pit mining for lithium-bearing spodumene is utilized in Australia, the world's largest lithium spodumene producer (Chan, 2022). Hard-rock lithium mining in China is used to extract both spodumene and lepidolite lithium sources (T. Gao et al., 2023), in order to reduce its reliance on foreign lithium minerals for lithium-ion battery manufacturing (Guo et al., 2021). Both methods of extraction are energy-intensive and environmentally damaging (Zheng, 2023). Lithium brine mining, while less carbon-intensive, has significant freshwater requirements, which are exacerbated by the arid nature of the region and potential water contamination during the brine concentration process (Lorca et al., 2022; Agusdinata et al., 2018). On the other hand, hard-rock lithium mining, although more carbon-intensive (Harvest, 2024), also demands vast quantities of water (Rock, 2023), and contributes to various forms of air pollution (Harvest, 2024). In general, these environmental impacts raise critical questions about the true cost of decarbonizing the transport sector through the transition from combustion vehicles to electric vehicles (EVs), which are perceived as being "clean" (Ghorbani et al., 2024).

This thesis paper therefore aims to empirically investigate the adverse environmental impacts of lithium brine and hard-rock mining in response to the policy-driven push towards EVs, by analyzing the experience of lithium mining in the regions where it occurs, in response to the implementation of the Paris Agreement in 2016. To implement the analysis, this study compiles unique panel data on a range of sophisticated environmental indicators and applies a synthetic control method (Andersson, 2019). The synthetic control method is used to construct a synthetic counterfactual, which is a weighted combination of all regions where lithium mining is not employed. The construction of a synthetic control group ensures that prior to treatment (The Paris Agreement), the regions without the presence of a lithium mine closely resemble those with mining operations, across several key predictors. Thereby, reducing the possibility of biased results, and increasing confidence that the results obtained are due to the intervention rather than pre-existing differences (Andersson, 2019).

Although standard statistical tests do not reject the parallel trends assumption, the synthetic control method offers particular advantages over the classic difference-in-difference (DID) estimator, as unobserved baseline variables like historical land use and geographical differences could impact emission concentrations prior to the implementation of The Paris Agreement (Kreif et al., 2016). Furthermore, the synthetic control method allows for the inclusion of key pre-treatment predictors such as the Human Development Index (HDI), precipitation, and relative humidity, on which each of the control units is weighed, in order to closely resemble the characteristics of the lithium mining regions (Andersson, 2019). Additionally, this method allows for the visualization of each control unit's contribution to the creation of the synthetic control (Andersson, 2019). A substantial limitation of the analysis conducted in this thesis paper refers to the extent of analysis possible within the available time period. While incorporating water scarcity and contamination into the analysis would have provided a more comprehensive picture of the adverse environmental impacts of lithium mining, this study provides in-depth results that are robust to a range of placebo tests.

The synthetic control method provides an estimated cumulative increase in CO_2 emissions of 284.7 metric tonnes in Western Australia and 12,924 metric tonnes in Antofagasta (Chile) during the post-treatment period. Although a series of placebo tests invalidated the results obtained in NOA (Argentina), CO_2 emissions in Sichuan (China) decreased by an average of 40,657 metric tonnes. This substantial decrease over the post-treatment period of 2016 to 2022, is in direct contrast to arguments made in the literature, (Harvest, 2024; Koščová et al., 2018). The decrease in CO_2 emissions in Sichuan (China) and the impact of the COVID-19 crisis, particularly on the Chinese export industry (Dyatkin & Meng, 2020), cast doubt on whether the reduction in CO_2 emissions purely stemmed from the Paris Agreement. The results of an additional robustness check accounting for the presence of the COVID-19 crisis indicated that this reduction in CO_2 emissions was induced by a reduction in lithium production due to the presence and effects of the COVID-19 crisis. The results for PM2.5 emissions further contrast a popular argument (Koščová et al., 2018). In Western Australia, PM2.5 emissions decreased by an average of 0.368 metric tonnes over the post-treatment period. On the other hand, PM2.5 emissions in Antofagasta (Chile) increased by an average of 3.16 metric tons, aligning with common expectations (Mas-Fons et al., 2024). In Sichuan (China), PM2.5 emissions experienced an average reduction of 10.6 metric tonnes.

Despite the rapidly growing scientific literature addressing the push for a green transition, focusing on the supply risks of lithium and the life-cycle analysis of battery production, there is a lack of literature that evaluates lithium mining (as required to power the green transition) and its environmental impacts on the regions in which this activity is conducted. Therefore, this thesis paper makes three main contributions to the existing literature. This paper's first contribution is twofold and builds on the idea of Peters et al., (2017), who investigate the sustainability of lithium-ion battery production, particularly in terms of the release of greenhouse gas (GHG) emissions, and suggests that in investigating the sustainability of lithium-ion battery production, other factors such as toxicity should be considered. However, their research primarily focuses on the battery production stage and does not relate lithium production to policy shifts. Not only does this thesis paper investigate the sustainability of lithium production in its initial stage of the supply chain, where lithium is mined (Peters et al., 2017), but secondly, it expands Peters et al., (2017) investigation by emphasizing that determining the sustainability of lithium production involves much more than the simple consideration of the release of GHG emissions. This thesis paper, although initially planning to investigate a range of environmental impacts such as water scarcity and contamination, still examines the release of PM2.5, a notable source of emissions in the lithium mining process, in addition to CO_2 (a form of GHG emissions).

Thirdly, while Agusdinata et al., (2018) focus on the environmental consequences of lithium production in the regions within which lithium mining is conducted, their research is primarily focused on the evolution of scientific research under this topic. In contrast, this thesis uses a quasi-experimental study (Andersson, 2019), to explore and quantify the effects of lithium mining on a range of environmental indicators within the actual regions where lithium is mined. Therefore, rather than just providing a theoretical argument (Agusdinata et al., 2018), this paper offers economic significance to the relationship under question. Furthermore, although Agusdinata et al., (2018) highlight the need for closer attention to the environmental effects of lithium mining on local communities, the paper does not discuss the potential policy implications of their findings. In order to support public policy it is essential to understand the environmental cost of lithium production. Understanding the true costs of decarbonizing the transport sector allows the Global North to implement stricter supply chain rules and regulations, targeting the initial stages of production rather than just the battery production level, as current policies implemented by the European Parliament, (2023) do.

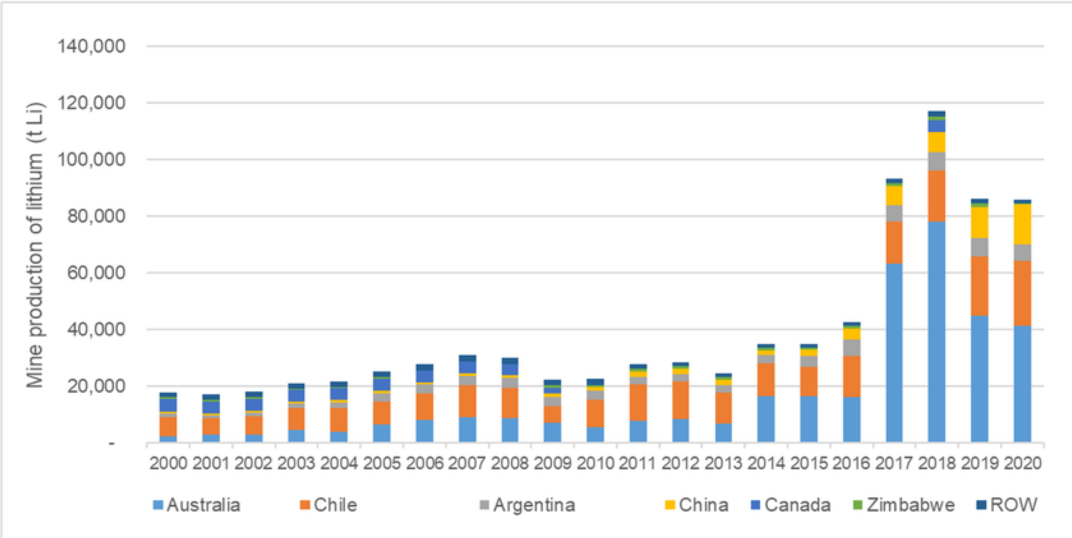
The remainder of this thesis is organized as follows. Section 2 provides background information on the process of both lithium brine and hard-rock mining in each of the four largest lithium-producing countries, namely, Argentina, Australia, Chile, and China, highlighting the largest lithium mines within each corresponding region, as well as a summary of the adverse environmental impacts that both forms of lithium mining induce. Section 3 outlines the data used and the empirical strategy followed. Section 4 presents the results obtained. Finally, Section 5 offers concluding remarks and discusses potential directions for future research.

II. Theoretical Background

1.1 Lithium production In Response to The Paris Agreement

The implementation of the Paris Agreement in 2016 (Horowitz, 2016), has resulted in the adoption of strategies, by the vast majority of the Global North, to increase the use of electric vehicles (EVs) between 2025 and 2050, in order to decarbonize the transport sector. These strategies have triggered a surge in demand for lithium-ion batteries, leading to a similar increase in the demand for lithium minerals, met primarily through an increase in lithium mining activities (**Figure 1)** (Ciftci & Lemaire, 2023; Petavratzi & Gunn, 2022).

FIGURE 1: GLOBAL MINE PRODUCTION OF LITHIUM, IN METRIC TONNES, FROM 2000-2020, BY COUNTRY



Note: The distribution of global lithium production, 2000–2020

Source: Petavratzi, E., & Gunn, G. (2022). Decarbonising the automotive sector: A primary raw material perspective on targets and timescales. *Mineral Economics*, *36*. https://doi.org/10.1007/s13563-022-00334-2

Figure 1 illustrates the evident surge in lithium production from 2016 onwards, which seems to be attributed to the successful implementation of the Paris Agreement in the same year (Horowitz, 2016). The resulting demand for lithium-ion batteries has reshaped global lithium production quantities, exhibiting an exponential increase from 2016-2018, alongside the improvement of extractive technologies (Harvest, 2024). Additionally, technological advancements made to increase the size and performability of lithium-ion batteries, have further contributed to the exponential increase in lithium production (Marchegiani et al., n.d.). To further illustrate the growing demand for lithium-ion batteries, the composition of lithium production used in batteries, increased from 23% in 2010 to 74% in 2021, reflecting the rapid change in global market dynamics of lithium (Bhutada, 2022). Furthermore, **Figure 1** highlights the main lithium-producing countries, namely Argentina Australia, Chile, and China, which account for most of the global supply.

1.2 Lithium Brine Mining

Lithium brine mining involves the process of pumping lithium-rich brine to the surface. The brine is pumped from bore fields drilled on the Salar and is directed into a series of evaporation ponds, through a network of pipelines, where it undergoes solar concentration (SeventhQueen & Chomsky, 2023). Brine concentration in the evaporation ponds separates and purifies the brine by filtering out other minerals such as sodium, potassium, and magnesium. After approximately 12 to 18 months the brine is concentrated and moved from the evaporation ponds to a processing facility (Katwala, n.d.), where it undergoes several chemical treatments to remove any remaining impurities and further increase the lithium concentration. The refined lithium solution is then converted into battery-grade lithium carbonate or lithium hydroxide (SeventhQueen & Chomsky, 2023; Fenix Lithium Mine, Salar Del Hombre Muerto - NS Energy, n.d.).

The South American lithium triangle **(Figure 2),** a region characterized by its notably arid environment, provides optimal conditions for an effective evaporation process, making lithium brine mining in this region relatively inexpensive, compared to other traditional mining methods (SeventhQueen & Chomsky, 2023). However, in the process of evaporation, more than 90% of the original water content is lost. Therefore, although the arid nature of this region allows for cost-effective extraction, the water-intensive process significantly impacts water scarcity in these mining regions (Vera et al., 2023; Katwala, n.d.). **Appendix A, Table 1** provides an overview of the lithium industry in each of the three countries that make up the South American lithium triangle. Furthermore, the table highlights the largest brine mining facilities operating within each of these countries. Namely, Salar del Hombre Muerto in Argentina, Salar de Uyuni in Bolivia, and Salar de Atacama in Chile. However, in the case of Bolivia, despite holding the world’s largest lithium reserve, it faces challenges in attracting overseas investment, to transfer this reserve into a lithium product. These challenges can mainly be attributed to Bolivia’s persisting political turmoil and instability (Berg & Sady-Kennedy, 2021).

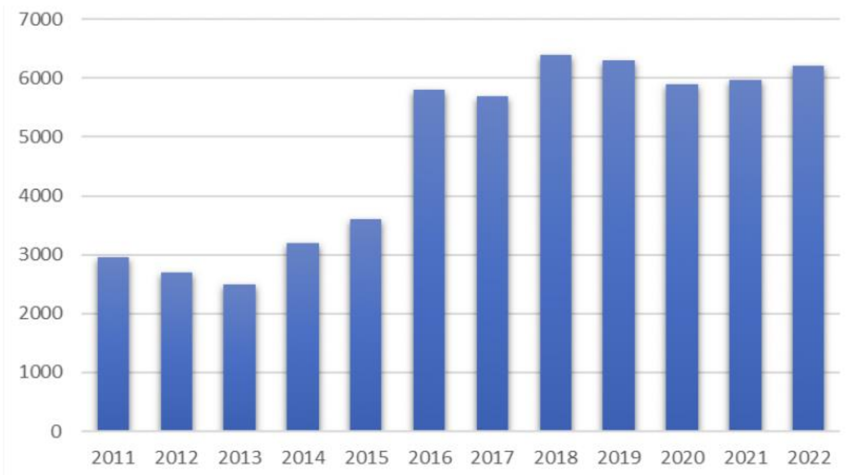
FIGURE 2:THE SOUTH AMERICAN LITHIUM TRIANGLE.

Note: The South American lithium triangle spans the bordering areas of Argentina, Bolivia, and Chile. The map highlights some of the major salt flats in which lithium brine is currently or is in the process of being mined.
Source: Janubová, B. (2023). Green Extractivism in Lithium Triangle. Slovak Journal of International Relations, 21, 109–134. https://doi.org/10.53465/SJIR.1339-2751.2023.2.109-134

1.2.1 Argentina

Argentina has been commercially extracting lithium since 1997 with the emergence of the Feniz lithium project in the Hombre Muerto slat falt, in the province of Catamarca. For decades this lithium brine mining site was Argentina's single lithium producer. However, given the spike in lithium demand since the adoption of EVs, Argentina has experienced a significant increase in lithium mining interests. In 2016 particularly, Argentina increased its global share of lithium production, with the launch of its second lithium brine extraction project, the Sales de Jujuy project (also known as The Olaroz Lithium Facility), located in the Olaroz salt flat in the province of Jujuy. The production of lithium from these two extraction facilities, together with the removal of taxes on exports, has fuelled further global interest in lithium brine mining in Argentina. According to a report from March 2017, the National Ministry of Energy and Mining counted 43 total lithium brine projects within Argentina (Marchegiani et al., n.d.). In 2018 Argentina experienced its peak lithium production level, which has since stabilized at about 6,200 metric tonnes **Figure 3** (Janubová, 2023). Furthermore, the figure below follows a similar trend to that of global lithium production in **Figure 1**, with a sudden increase in lithium production in 2016, although this increase is not "exponentially".

FIGURE 3: TOTAL MINE PRODUCTION OF LITHIUM IN ARGENTINA (IN METRIC TONNES)



Note: Lithium mine production in Argentina experienced a spike in 2016 until its peak in 2018. Lithium production then stabilized from this period onwards.

Source: Janubová, B. (2023). Green Extractivism in Lithium Triangle. Slovak Journal of International Relations, 21, 109–134. https://doi.org/10.53465/SJIR.1339-2751.2023.2.109-134

1.2.1.1 Salar del Hombre Muerto

The Fenix project or the Fenix lithium mine, is a brine mining and lithium processing facility situated in the Salar del Hombre Muerto salt pan in Argentina and has been in operation for over 25 years. This facility is owned and operated by Minera del Altiplano, a local Argentinian operating subsidiary of the Philadelphia-based chemical manufacturing company, Livent (Fenix Lithium Mine, Salar Del Hombre Muerto - NS Energy, n.d.). The lithium brine, once extracted from the facility is then transported by road to a processing plant for the production of lithium carbonate. This carbonate is then transported by road to ports in both Argentina and Chile (Fenix Lithium Mine, Salar Del Hombre Muerto - NS Energy, n.d.). Livent has however recently come under scrutiny regarding their rights to extract freshwater from the Trapiche River, which local and

Indigenous communities are heavily dependent on. This concern is in response to the significant depletion of the river given the vast water requirements of lithium brine mining in this area, as well as the site's planned expansion (Fenix Lithium Mine, Salar Del Hombre Muerto - NS Energy, n.d.; Ángel, 2022).

1.2.1.2 Salar de Olaroz

The Sales de Jujuy project or the Olzaroz Lithium facility, was the second lithium extraction project in the region which initially started operating in 2015 (Marchegiani et al., n.d.). This facility is located in the Jujuy Province of Northern Argentina, approximately 230 kilometres northwest of the capital city of Jujuy. It began as a joint venture between Toyota Tsusho Corporation (TTC), and Jujuy Energia y Mineria Sociedad del Estado (JEMSE) which is a mining investment company owned by the Jujuy provincial government (Marchegiani et al., n.d.). Despite the establishment of the joint venture in 2010, when the company submitted its initial environmental report, the project faced delays due to certain additional requirements. Eventually, lithium brine mining at this facility, took place in 2015, with the production of 11, 845 tonnes of lithium carbonate in 2016 (Marchegiani et al., n.d.). However, unlike other lithium brine mining facilities, the Olaroiz lithium facility does not contain contamination infrastructure, known as a tailing facility, which essentially is required to store waste. Water from the production process is instead immediately fed back into the ponds, where the salt waste is harvested every three years (OLAROZ LITHIUM FACILITY, 2021; Marchegiani et al., n.d.).

1.2.2 Chile

Despite possessing much fewer lithium reserves compared to both Argentina and Bolivia, Chile has the world's largest commercially viable lithium resources. More specifically, the Salar de Atacama, located in Northern Chile, is the world's largest and highest-grade producer of lithium from brine sources (Berg & Sady-Kennedy, 2021). Furthermore, situated within the driest desert on earth, these extremely arid conditions accelerate the evaporation process, providing lithium mining in this region its cost-effective nature. The solar evaporation process concentrates lithium salts in the brine, which are then transferred to the following ponds within the system. This process is repeated until the lithium reaches its desired level of concentration (about 6%), suitable for converting into lithium carbonate (Berg & Sady-Kennedy, 2021). Chile's lithium industry is largely dominated by two major companies, Albemarle, a U.S.-based company that also operates in

Australia, and Sociedad Quimica y Minera de Chile (SQM), which is Chile’s largest lithium mining company (Berg & Sady-Kennedy, 2021). These companies are allowed to operate and extract brine, via a lease agreement, administered by state-owned Corporacion ´ de Fomento de la Produccion ´ (CORFO) (Palandrani, 2023).

SQM which operates the largest lithium brine mine in Chile, is also one of the world’s leading fertilizer companies, initially focusing on producing potassium nitrate, from sodium nitrate and potassium chloride (SQM, 2021). In search of scarce potassium chloride, SQM discovered and ventured into the lithium industry, driven by competitive lithium prices, as early as 1996. Although lithium was initially a secondary product, its success led to the development of the first lithium processing plant in Salar del Carmen, near Antofagasta City, where lithium brine is processed into lithium carbonate to be sent to battery manufacturers (SQM Lithium, 2023; Palandrani, 2023). However, SQM’s Salar de Atacama lithium project operates in close proximity to indigenous communities, who own the land surrounding this mine, but are left struggling to secure water resources. Conflicts between these Indigenous communities and SQM are not a new occurrence, but date back to 2007, when a government-commissioned study revealed that SQM was contributing to significant water depletion, by extracting about 750-1,950 litres per (EARTHWORKS, 2020).

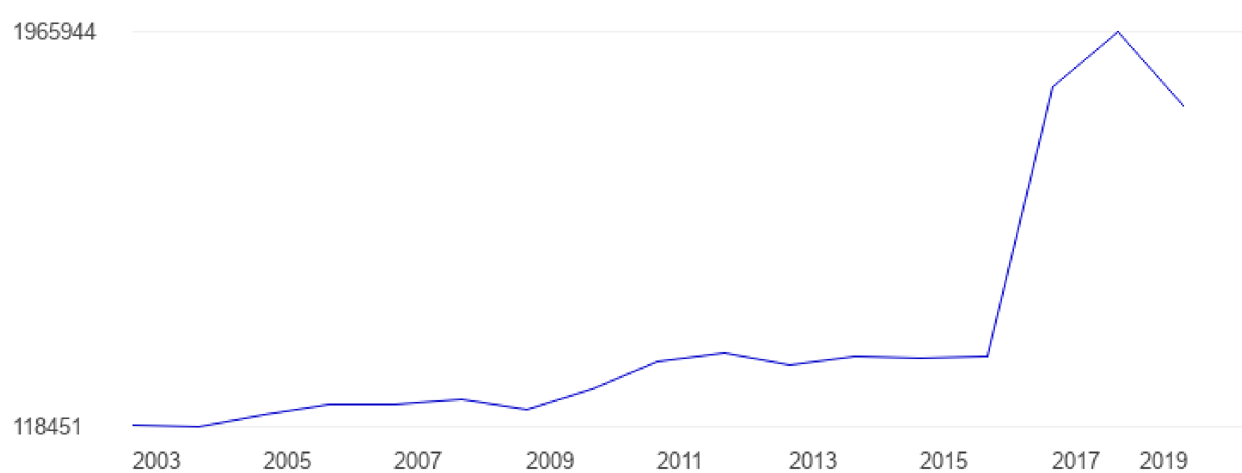
1.3 Hard-Rock Lithium Mining

1.3.1 Australia

Lithium resources are mainly contained in brine or pegmatite deposits. Lithium deposits contained in brines mainly include underground and slat-lake brine, while pegmatite-type lithium deposits are stored in lithium-bearing minerals such as spodumene, lepidolite, petalite, and zinnwaldite (T. Gao et al., 2023). Western Australia utilizes a method of hard-rock lithium mining to extract lithium-bearing spodumene which can be processed into lithium carbonate and/or lithium hydroxide (namadmin, 2019). Hard-rock lithium mining is a form of traditional open-pit mining, which involves blasting and excavating lithium-bearing ore from a quarry. Once extracted, this ore undergoes a process of heating at an extremely high temperature, in order to separate spodumene from other minerals found in the extracted ore (Harvest, 2024). After the ore is cooled, the remaining amount is re-milled and cooked with sulphuric acid, in a process known as acid leaching (hpprocess, 2023), to remove any remaining impurities (Harvest, 2024). The spodumene is then further processed into spodumene concentrate which is packaged and shipped to China where it undergoes further processing to produce lithium hydroxide, a crucial substance in batteries (Talison Lithium, n.d.; namadmin, 2019).

Western Australia is the world's largest provider of lithium spodumene, experiencing peaking quantities in 2018 (**Figure 4).** This production is responsible for more than half of the global lithium supply. In particular, the Greenbushes lithium mine alone produces 22% of global lithium production (Chan, 2022). This mine is situated directly south of Greenbushes town, approximately 250km South of Perth, a major shipping port (Overview, n.d.). The Greenbushes lithium mine is owned and operated entirely by the Talison Lithium Australia joint venture, in which the Albermarle Corporation owns 49% and Tianqi Lithium Energy Australia (TLEA) owns 51% (Daly, 2020). Talison Lithium has been mining lithium spodumene from the Greenbushes mine since 1983, which makes it the longest and continuously operating lithium mine in Western Australia. However, the proximity of the Greenbushes mining site to the neighbouring town has pushed the town's boundaries to the very edge of the mine pit (Cargill, n.d.).

FIGURE 4: ANNUAL LITHIUM PRODUCTION IN AUSTRALIA (IN METRIC TONNES)



Note: In 2016, Australia experienced an exponential increase in lithium production, peaking in 2018 and then exhibiting a slight decrease.

Source: Australia Lithium production—Data, chart. (n.d.). TheGlobalEconomy.Com. Retrieved May 16, 2024, from https://www.theglobaleconomy.com/Australia/lithium_production/

While a vast number of lithium mines in Western Australia are still in their developmental stages, two other major hard-rock lithium projects are in the process of initiating operations in the region. Namely, the Woodinga Lithium project and the Mount Marion lithium project. The Wodgina Lithium project is situated approximately 120 km south of Port Hedland in the Pilbara region of Western Australia, from which Woodinga plans to export its processed spodumene to China. This project operates under MARBL JV, a joint venture between MinRes (40%) and the Albemarle Corporation (60%) (Barich, 2023), Although the Woodinga lithium project was expected to initiate production in 2019 (Barich, 2023), it faced a two-year delay and then resumed production in 2021, in response to soaring global lithium demand, aiming to have produced its first batch of processed lithium spodumene by May 2022 (Lamberti, 2018).

The Mount Marion lithium project, which is situated approximately 40 km southwest of Kalgoorlie, in the Goldfields region of Western Australia, is a joint venture between MinRes (50%) and one of the world's largest lithium hydroxide providers, Jiangxi Ganfeng Lithium Co. Ltd. (50%) (Rani, 2023). MinRes which manages both the lithium mine and the corresponding lithium processing facility, yields a comparable spodumene concentration to the Woodinga project, of 6%. The processed spodumene is then transported by road to the Port of Esperance, where it is exported (*Lithium*, n.d.). In 2023, lithium-bearing pegmatite deposits were discovered approximately one kilometre below the surface, leading to the announcement of plans to double explorative drilling and begin producing lithium spodumene in 2024 (Thomson, 2023; Reporter, n.d.).

1.3.2 China

China plays a major role in the lithium-ion battery (LIB) market, through its dominant position as the world's largest LIB manufacturer, alongside its control of over 70% of global lithium production (Altiparmak, 2023). Additionally, China holds a significant amount of lithium reserves within its borders, but due to national exploitation and development limitations, has not been able to transform this reserve into commercially marketable lithium. Therefore, China's lithium-ion battery market is heavily dependent on foreign lithium resources to bridge the gap between demand and supply. The risks posed by such dependence are reflected in the spot price of lithium carbonate, which increased by 300% in 2017, compared to previous years, due to a temporary shortage of lithium spodumene supply from Australia (Guo et al., 2021; Gu & Gao, 2021).

Nevertheless, lithium production in China largely takes place in the form of hard-rock lithium mining from both spodumene and lepidolite sources, each of which are significant sources of lithium, producing a concentration of about 8%, and 7.7%, respectively (T. Gao et al., 2023). This hard-rock lithium mining is carried out at Jiajika mine, which is currently the largest hard-rock lithium mine in Asia, mining lithium from 2009 to 2013, with a complete suspension of mining activities in 2019 (J. Gao et al., 2022). The Jiajika mine is situated at the intersection of Kangding County, Yajiang County, and Daofu County. Despite the vast amount of lithium deposits, the Minyak Lhagang (Jiajika) yields a lithium concentration as low as 2%. This means that a large amount of lithium-bearing ore needs to be mined to compensate for this low concentration, after which the extracted lithium minerals are transported 600 kilometers for a final stage of processing at Dartsedo/Kangding (Zhang et al., 2022).

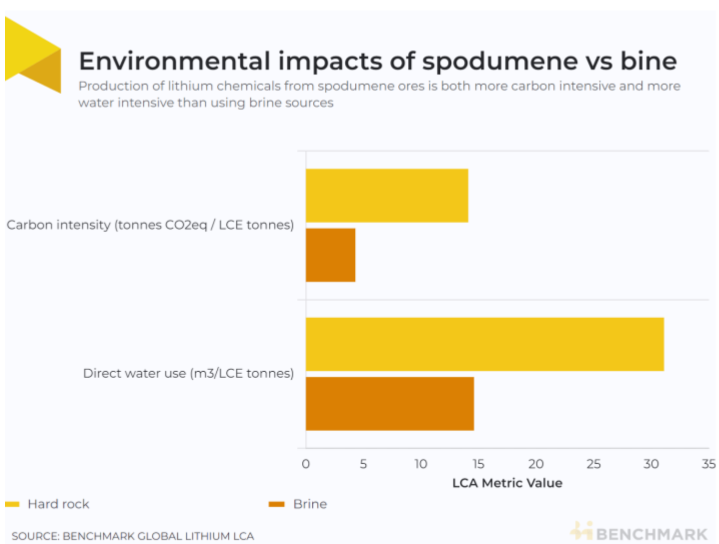
1.4 The Environmental Impacts of Lithium Extraction

Government officials across the three states that make up the lithium triangle have emphasized the strategic importance of lithium in providing economic opportunities and growth while simultaneously promoting the “sustainable” nature of lithium extraction. Seeing lithium as a key global resource in fighting climate change has been used to justify and even legitimize these lithium extraction projects, which can explain the perception of lithium extraction as sustainable. A second reason for such perception also stems from its comparatively less impactful nature when compared to other forms of fossil mining. Generally, the negative environmental impacts of lithium extraction are overlooked due to the idea of it being "cleaner" (Janubová, 2023). Although the emissions resulting from both methods of lithium production, namely lithium brine production and hard-rock lithium production, are lower than the emissions resulting from fossil fuel production, both methods of lithium mining are energy intensive, and lead to other important environmental impacts such as air and water pollution as well as water scarcity in the particularly arid regions within which lithium mining facilities are located (Zheng, 2023).

1.4.1 Impact of Lithium Mining on Emissions

Lithium production from ore sources like spodumene is argued to release three times more carbon dioxide (CO2) into the atmosphere, compared to lithium mining from brine sources **(Figure 5)** (Harvest, 2024). The energy-intensive nature of hard-rock lithium mining can be attributed to the previously described processes of drilling, blasting, milling, and cooking (hpprocess, 2023). More specifically, the drilling and blasting activities, which take place in and around quarries, contribute to the release of gasses and solid particles into the atmosphere. These gasses and solid particles, according to the CDC, (2023), are sources of particulate matter (PM) or particulate pollutants. PM2.5 refers to inhalable solid particles with a diameter of about 2.5 microns smaller (US EPA, 2014; US EPA, 2016). Apart from drilling and blasting, activities such as the loading and unloading of operations, movements of heavy trucks on unpaved roads, and the general operation of energy-intensive machinery required for spodumene processing, contribute to the release of both PM2.5 emissions and greenhouse gas (GHG) emissions, primarily in the form of Carbon Dioxide (CO2) (Koščová et al., 2018). It is estimated that for every tonne of lithium spodumene produced, 15 tonnes of CO2 are released while contributing a smaller amount of dust (PM2.5) emissions (Talison Lithium, 2018).

FIGURE 5: THE ENVIRONMENTAL IMPACTS OF LITHIUM BRINE VS HARD-ROCK LITHIUM MINING

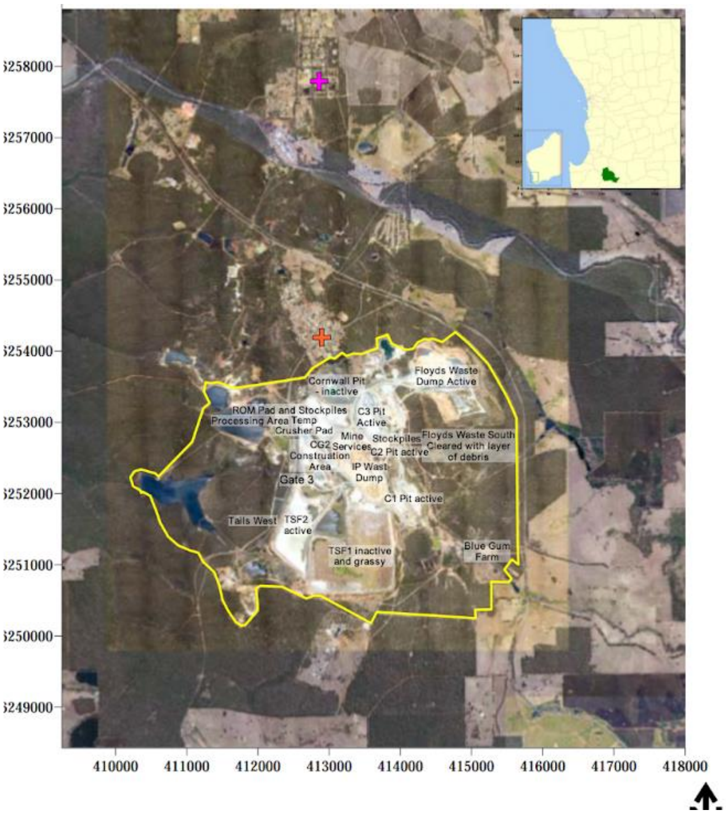


Note: Hard-rock lithium mining for spodumene is both more carbon and water-intensive. Emitting about three times more CO2eq/LCE tonnes and using about double the amount of water (m3/LCE tonnes)

Source: Hard rock lithium vs. Brine—How do their carbon curves compare? (2023, March 3). Benchmark Source. https://source.benchmarkminerals.com/article/hard-rock-vs-brine-how-do-their-carbon-curves-compare

Taking the case of Greenbuses lithium mine in Western Australia, a recent dust emissions report has raised some concerns ahead of the mine's expansion plans. Situated directly South of the Greenbushes-Bridgetown, the mine is in remarkable proximity to this community as marked by the red cross, with the mine boundary marked by the yellow outline in **Figure 6** below (Talison Lithium, 2018; Cargill, (n.d.) who wrote an article regarding the hazardous effects of Greenbushes mining operations, already in 1997, detailed its impact on the local community of Greenbushes-Bridgetown. This article describes an occurrence of a blue-white haze caused by carbon monoxide, and the spread of radioactive dust throughout the town, as a result of explosive mining activities (Cargill, n.d.) Additionally, due to the location of the explosive site within Greenbushes mine and the airborne nature of particulate matter (PM), which can travel hundreds to thousands of miles, and remain in the air for weeks, the operation of hard-rock lithium mines like Greenbushes and others in Western Australia pose a clear risk to nearby communities (Talison Lithium, 2018;US EPA, 2016;US EPA, 2014).

FIGURE 6: GREENBUSHES LITHIUM MINE SITE



Note: The area that makes up the Greenbushes lithium mine is marked by the yellow outline. The graph illustrates the close proximity of the Greenbushes-Bridgetown (marked by the Red Cross) to the mien site. Source: Talison Lithium. (2018). Appendix G - Talison Greenbushes Expansion Dust Impact Assessment.pdf. Retrieved May 7, 2024, from https://www.epa.wa.gov.au/sites/default/files/Referral_Documentation/Appendix%20G%20-%20Talison%20Greenbushes%20Expansion%20Dust%20Impact%20Assessment.pdf

On the other hand, lithium brine mining, which harnesses solar energy in the notably arid regions that make up the South American Lithium Triangle, makes the production process much less energy-intensive compared to the method of hard-rock lithium mining for spodumene **(Figure 5)** (Kelly et al., 2021). This method, however, is not emissions-free, as greenhouse gas (GHG) emissions, primarily in the form of CO2 emissions are released into the atmosphere from the combustion of high diesel requiring, powerful machinery that pumps brine and freshwater from the Salar, to the surface, into evaporation ponds. Furthermore, given the substantially lower concentration of lithium brine sources, compared to spodumene, a greater amount of brine has to be extracted in order to produce the same amount of lithium concentrate (Mas-Fons et al., 2024).

1.4.2 Impacts of Lithium Mining on Water Scarcity and Contamination

Despite the popular discourse that lithium brine mining from salt flats is a relatively “clean” extraction process compared to the more visually harming or impactful method of hard-rock lithium mining, it has devasting effects on water availability and water safety. Specifically in the immensely arid regions of the lithium triangle (Lorca et al., 2022). Lithium brine mining requires vast quantities of groundwater from subterranean reserves in order to pump brine into surface evaporation ponds using a network of pipelines (SeventhQueen & Chomsky, 2023). Given the already arid nature of regions within this Lithium Triangle, where the average annual precipitation is less than 100mm, the global race of powerful international companies to secure lithium brine extraction rights in the salt flats, in direct response to the unprecedented global lithium demand, is exacerbating the effects of water scarcity on local communities who reside near these mines. Beyond the already occurring climate-change-induced droughts (Press, 2024; Ángel, 2022). To illustrate, companies like SQM in Chile, pump at least 1,2890 liters of groundwater per second, transferring lithium-concentrated brine from one pool to another (Press, 2024). Similarly, within the first three years of operation at the Fenix project (Salar de Hombre Muerto), a dam on the Trapiche River completely dried up due to the project’s groundwater withdrawals and requirements, leading to the loss of 16 to 20 hectares of fertile land (Press, 2024). More notably, the depletion of local water sources has rendered certain indigenous lands unfarmable, on which these communities are heavily dependent, for subsistence crops like quinoa (Simon & Messad, 2023).

Not only are the lives of local and indigenous communities threatened by their inability to access fresh water, but the issue is compounded by the contamination of the little freshwater still available, by lithium brine mines in the region. More specifically, this contamination occurs due to toxic chemical leaks. The shallow, PVC-lined ponds in which the evaporation process takes place must be perfectly sealed to prevent any leakage of chemical substances, (especially during the cleaning process) which can contaminate water supplies (Agusdinata et al., 2018). Even if perfectly sealed, other chemicals and metals that are a by-product of brine production can run off from evaporation ponds into local water sources, poisoning local ecosystems and populations (Energy, 2024). Although brine water can be recycled back into the salt flats, it can interact with freshwater systems, contaminating it. Rendering the water used in the lithium brine mining processes as fossil water (Simon & Messad, 2023). Despite the evidence of contamination of local water bodies, based on interviews with nearby communities, these environmental impacts are heavily underreported. For instance, Camilo Condorí, a 63-year-old man living near Salar de Hombre Muerto, close to Livent's Fenix lithium project, explains that before the lithium mine's presence, he could drink water directly from a nearby spring. He goes on to explain that the water now makes him sick in spite of company claims that the water is safe and uncontaminated (Ángel, 2022).

While lithium brine mining has received significant media criticism for its mass consumption of water, a life-cycle assessment analysis (LCA) revealed that lithium spodumene mining is more water-intensive than lithium brine mining **(Figure 5).** Hard-rock lithium mining for spodumene requires vast quantities of water for dust suppression in the blasting process (Rock, 2023), as well as for various chemical processes, in order to separate spodumene from other minerals in the ore. Water is further required to wash and rinse the processed minerals to remove any remaining impurities (Harvest, 2024; Lithium Liabilities, n.d.). This freshwater requirement, similar to lithium brine mining, contributes to the depletion of local water sources, impacting the water availability for surrounding communities and ecosystems, especially considering the use of high-quality freshwater in the production process, after which it becomes contaminated, and cannot be reused (Rock, 2023; Evans, 2020). Furthermore, hard-rock lithium mining for spodumene also occurs in particularly arid regions, which exacerbates local water stress (Kronbauer, 2022). Therefore, while a crucial resource for the mining process, water is growing increasingly scarce in Western Australia, raising concerns about the effects of the ongoing drought not only on local ecosystems but also on the mining industry itself (Evans, 2020). However, although lithium spodumene mining is comparatively more water-intensive, the arid nature of Western Australia cannot compete with that of the regions in which lithium brine mining takes place, enhancing the overall impact on water scarcity (Berg & Sady-Kennedy, 2021).

Water contamination in the case of hard-rock lithium spodumene mining usually results from ore processing methods, which include acid leaching and the subsequent production of tailings. The process begins with roasting the ore to remove significant impurities. In order to produce the desired concertation of lithium, the ore has to be treated with a range of highly concentrated acids, such as sulphuric and hydrochloric acid, which occurs in the acid-leaching process. The lithium recovery rate depends on the acid concentration. Therefore reaching high rates of about 8% requires intense acid concentrations (Dolma, 2016; Gao et al., 2023). Additionally, a large amount of sodium hydroxide is needed to remove sulphate ions from the solution, generating additional solid waste, all of which results in tailing, which are the waste materials remaining after lithium has been extracted from the ore (Lappalainen et al., 2024; Baker et al., n.d.). These mine tailings which consist of a combination of water, rock, and chemicals, are often stored in tailings facilities (Baker et al., n.d.). However, the chemical waste stored in the tailing facilities can still penetrate the soil and water, poisoning local ecosystems (Intelligence, 2023). An example of such contamination to both the soil and local water sources, and the corresponding impact on local communities, is the case of Ganzizhou Rongda Lithium in Dartsedo. This lithium spodumene processing facility, as part of the Jiajika mine, released toxic chemicals into the Lichu River, contaminating the water and killing fish and farm animals that belong to the local communities relying on this river (Dolma, 2016; Denyer, 2023). Despite investigative reports claiming the mine or plant was not responsible (Denyer, 2023).

Considering once again Greenbushes lithium mine illustrated in **Figure 6** depicted in the top right corner of the mine's boundary, is Floyd's waste dump. Located in such close proximity, there is little doubt that tailings and other waste could impact Greenbushes-Bridgetown. Although concerns regarding groundwater contamination remain unaddressed, the mine produces approximately 600,000 tonnes of waste material per year, compared to the 1.5 million tonnes of spodumene produced annually (Young, 2019; Talison Lithium, 2018).

III. Methodology

1.5 Data

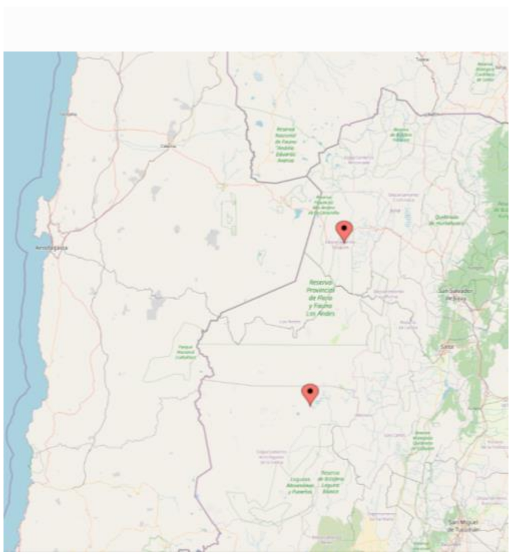
In order to explore the environmental impacts of lithium mining, this study compiles panel data on sophisticated environmental indicators, such as CO2 and PM2.5 emissions. The full sample used consists of all subnational regions (NUTS-2 level[1]), within the four main lithium-producing countries, from the period 2000-2022, given the most recently available data. The implementation

[1] NUTS 2: basic regions for the application of regional policies
Source: *Overview—Eurostat*. (n.d.). Retrieved June 25, 2024, from https://ec.europa.eu/eurostat/web/nuts

of the Paris Agreement in 2016 provides a pre-treatment period of 16 years and a post-treatment period of 6 years (Andersson, 2019). The treatment group consists of regions with active lithium mines, while the control group includes regions without a lithium mine. More specifically, the treatment group consists of the NOA province in Argentina, the Western Australia province in Australia, the Antofagasta province in Chile, and the Sichuan province in China. The coordinates of the lithium mines within the regions specified are depicted below in **Figure 7.**

FIGURE 7: LITHIUM MINE SITE COORDINATES

Fig7a. Argentina, NOA province[2]



Note: The top marker indicates the location of the Salar de Olaroz lithium mine (23.4747°S 66.6658°W), and the bottom the Salar del Hombre Muerto lithium mine (25°21′S 67°04′O)

Fig 7b. Western Austrailia pronvince, Austrilia[3]

Note: The top marker indicates the location of Woodinga mine (21°10′52″S 118°40′31″E) the second bottom indicates Mount Marion (31° 4' 28"S, 121° 27' 48"E) and the bottom Greenbushes lithium mine (33°51′33″S 116°03′20″E).

[2] Sources include: (Salar de Olaroz) Salar de Olaroz mine, Salar de Olaroz, Susques, Susques Department, Jujuy Province, Argentina. (n.d.). Retrieved June 15, 2024, from https://www.mindat.org/loc-310991.html

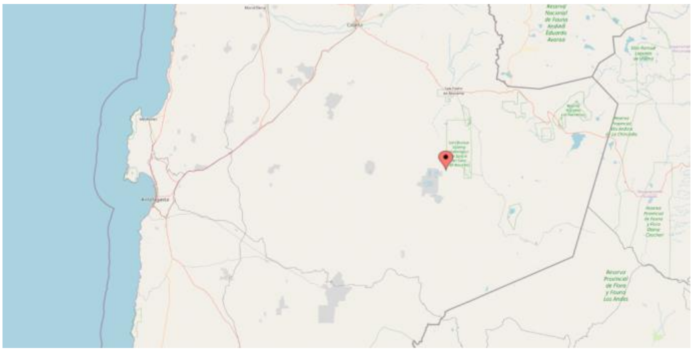
(Salar del Hombre Muerto) Salar del Hombre Muerto, Argentina. (n.d.). Retrieved June 15, 2024, from https://www.mindat.org/loc-229832.html

[3] Sources include: (Woodinga) Latitude.to. (n.d.). GPS coordinates of Wodgina mine, Australia. Latitude: -21.1811 Longitude: 118.6752. Latitude.to, Maps, Geolocated Articles, Latitude Longitude Coordinate Conversion. Retrieved June 15, 2024, from http://latitude.to:8080/articles-by-country/au/australia/127881/wodgina-mine

(Mount Marion) PorterGeo Database—Ore Deposit Description. (n.d.). Retrieved June 15, 2024, from https://portergeo.com.au/database/mineinfo.asp?mineid=mn1543

(Greenbushes) Greenbushes Mine, Greenbushes Tinfield, Bridgetown-Greenbushes Shire, Western Australia, Australia. (n.d.). Retrieved June 15, 2024, from https://www.mindat.org/loc-11514.html

Fig 7c. Chile, Antofagasta province[4]



Note: Salar de Atacama (SQM) lithium mine (23°28'36"S 68°20'57"W). Located in Northern Chile near the borders of Argentina and Bolivia.

Fig7d. China, Sichuan Province[5]

Note: Jiajika lithium mine (30.296°N 101.302°E), is located in Sichuan Province but also in close proximity to the Tibet province.

1.5.1 Emissions data

Hard-rock lithium mining involves processes of drilling and blasting to extract lithium-bearing ore, which releases significant amounts of dust particles into the atmosphere. Proceeding activities such as the loading and unloading of operations, movements of heavy trucks on unpaved roads, and the

[4] Sources include: (SQM) Garcés, I., & Alvarez, G. (2020). WATER MINING AND EXTRACTIVISM OF THE SALAR DE ATACAMA, CHILE (p. 199). https://doi.org/10.2495/EID200181

[5] Sources incldue: (Jiajika) Jiajika Mine, Kangding pegmatite field, Kangding County, Garzê Autonomous Prefecture (Ganzi Autonomous Prefecture), Sichuan, China. (n.d.). Retrieved June 15, 2024, from https://www.mindat.org/loc-146947.html

general operation of energy-intensive machinery required for spodumene ore processing, all contribute to the emissions of both PM2.5 particles and carbon dioxide (CO2) (Koščová et al., 2018). Lithium brine mining on the other hand, although utilizing solar energy also results in CO2 emissions due to the high diesel consumption of machinery used to pump brine and freshwater from the Salar, into surface ponds (Kelly et al., 2021; Mas-Fons et al., 2024). Additionally, since brine has a lower lithium concentration compared to spodumene, a much larger volume of brine is required to produce the same amount of lithium concentrate (Mas-Fons et al., 2024). Both CO2 and PM2.5 emissions data, measured in metric tonnes, were obtained from the EDGAR database. EDGAR provides emissions data at a 0.1 x 0.1 degree resolution (*EDGAR - The Emissions Database for Global Atmospheric Research*, n.d.).

1.5.2 Key Predictors Data

1.5.2.1 CO2 Emissions

Given the importance of energy use in order to achieve human development, particularly in regard to the social aspects (Costa et al., 2011), the Human Development Index (HDI) is included as a key predictor in constructing a synthetic counterpart for the previously specified mining regions. Including HDI as a key predictor in the analysis of CO2 emissions ensures that the synthetic control unit closely matches the treated region (Abadie & Vives-i-Bastida, n.d.). This data was obtained from The Global Data Lab[6] at Radboud University and is a translation of the UNDP's official HDI.

1.5.2.2 PM2.5 Emissions

Relative humidity (RH), which is the ratio of water vapor[7] relative to saturation (Ardizzone, 2023), causes the size of PM2.5 particles to increase, trapping the polluted air particles closer to the ground, impacting the dispersion of particles and thereby increasing the concentration of PM2.5 emission (J. Wang & Ogawa, 2015). In order to account for the positive effect that RH has on PM2.5 emissions (Yang et al., 2017), the annual average relative humidity (%) is included as a

[6] HDI data ranges from 200-2021, data for the year 2022 was obtained through a process of linear interpolation

[7] Water vapour- The amount of moisture in the atmosphere. The faster the rate of evaporation, the more moisture in the atmosphere. Hausfather, Z. (2018, January 19). Explainer: What climate models tell us about future rainfall. Carbon Brief. https://www.carbonbrief.org/explainer-what-climate-models-tell-us-about-future-rainfall/

predictor variable in the creation of a synthetic control. Additionally, the presence of precipitation has been found across the literature to reduce the concentration of PM2.5 emissions in the atmosphere, as precipitation suppresses and clears PM2.5 and other pollutants (R. Wang et al., 2023). Therefore, the total yearly precipitation (mm) is included as a second key predictor of PM2.5 emissions. Both precipitation and relative humidity data were obtained from The Global Data Lab at Radboud University, based on ERA-5[8] estimates at a spatial resolution of 0.25° x 0.25° (Copernicus Climate Change Service, 2019).

1.6 Empirical Strategy

1.6.1 Synthetic control group method

The aim of this paper is to investigate the adverse environmental impacts of lithium mining, focusing on both lithium brine and hard-rock lithium mining methods. In doing so, this study compares CO2 and PM2.5 emissions within regions in which these mines are located, to regions without mines, analyzing data from both before and after the implementation of the Paris Agreement in 2016 (Bouttell et al., 2018), which has led to the expansion of lithium mining operations in order to meet the rising demand for lithium-ion batteries (Ciftci & Lemaire, 2023). This has led to a notable exponential increase in global lithium production quantities between 2015 and 2016 **(Figure 1) (**Harvest, 2024)**.**

To implement the analysis, a synthetic control method (SCM) is employed (Clarke et al., 2023). The main idea of this method is to create a synthetic counterpart for each region in the treatment group (regions with a lithium mine), which is constructed by assigning weights to each of the regions in the control group (regions without a lithium mine). The weights are chosen in a way that optimizes the similarity between the synthetic control group and the treatment group, according to pre-treatment characteristics. Allowing for the comparison of effects between the treated and synthetic control units (Acemoglu et al., 2016).

[8] ERA-5: ERA5-Land is a global land-surface dataset consistent with atmospheric data from the ERA5 reanalysis from 1950 onward
Source: Copernicus Climate Change Service. (2019). *ERA5 monthly averaged data on single levels from 1940 to present* [dataset]. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). https://doi.org/10.24381/CDS.F17050D7

A difference-in-difference (DID) estimator compares differences in outcomes over time between the treatment and control group by calculating the differences in outcomes before and after the intervention (Doudchenko & Imbens, 2016). Core to DID is the assumption of a parallel trend between the treatment and the control group both before and after the intervention. Assuming any differences in outcomes between the treatment and control groups after the intervention are purely due to the intervention itself and not due to any pre-existing trends or differences in the groups (Marx et al., 2024). The synthetic control group method addresses exactly this issue by creating a unique synthetic control for each treated unit, accounting for variations in pre-existing trends (Abadie et al., 2015). In summary, by using the synthetic control group method, this study aims to isolate the environmental impacts of this increased lithium mining, such as CO2 and PM2.5 emissions (Abadie et al., 2015).

Let J +1 be the number of regions within the four main lithium-producing countries of Argentina, Australia, Chile, and China, indexed by j, among which j = 1 denotes the regions within each of these countries in which lithium mining is active, the “treatment group”. The “donor group” refers to the regions within these countries without lithium mines, denoted by j = 2 to j = J +1. The “treatment group” is exposed to the intervention in periods $T_0 + 1, \ldots T$, and the pre-treatment period is defined as t =1,2,…T_0, during which none of the units received the intervention. This period then serves as the baseline for constructing the synthetic control (Andersson, 2019; Abadie et al., 2015). The synthetic control group is constructed as a weighted average of the donor pool j = 2 to j = J +1, and can be represented by a vector of weights W = (w2,…, wJ+1)′ with 0 ≤ w j ≤ 1for j = 2,...J and w2 +⋯+wJ +1 = 1 (Abadie et al., 2015; Andersson, 2019). Weights (W) are chosen to minimize the difference between the treatment and synthetic units, across several key predictors of the outcome variable (Andersson, 2019).

Key predictors include the Human Development Index (HDI) for CO2 emissions and precipitation and humidity for PM2.5 emissions. The level of a country's HDI is seen in literature to be closely related to emissions of CO2 (Fu et al., 2020), and both precipitation and relative humidity (RH) are found to be strong determinants of PM2.5 emissions (Wang & Ogawa, 2015; Wang et al., 2023). Finally, a one-year lag to CO2 and PM2.5 emissions are included as key predictor variables, to account for the time required for lithium to be mined, processed, and concentrated (Katwala, n.d.). If the creation of the synthetic control group is able to reproduce a very similar trend to the treatment regions in terms of CO2 and PM2.5 emissions, before the introduction of the Paris Agreement (the intervention), it will mean that the important factors influencing these environmental impact measures have been captured. Therefore, any changes observed after the intervention period can be attributed to the Paris Agreement itself, rather than some unobserved factors (Andersson, 2019).

IV. Results

1.7 CO2 Emissions

Figures 8a-d illustrate the trajectory of CO2 (metric tonnes) emissions from both lithium brine and hard-rock mining regions within Argentina, Australia, Chile, and China, compared to the control group averages, from 2000 to 2022. Overall, before 2016, CO2 emissions in each major lithium mining region follow a similar trend to the average of their corresponding control group. This is most notable in NOA (Argentina) and Antofagasta (Chile). Whereas in Western Australia and Sichuan (China), the trend is substantially smoother compared to the average of the donor pools (Andersson, 2019).

Fig8a. Path plot of CO2 Emissions during 2000:2022
NOA vs Average of 6 donor regions Argentina

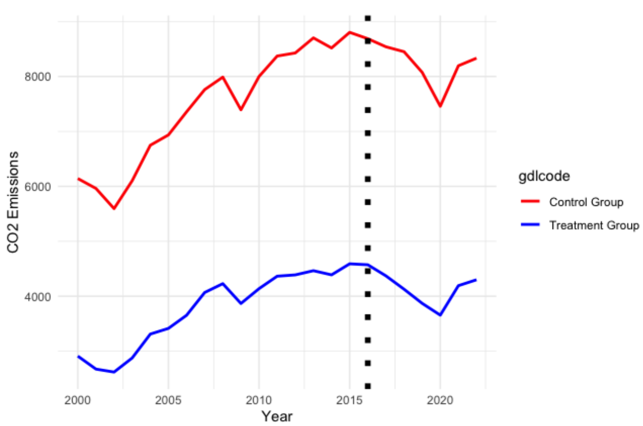


Fig8b. Path plot of CO2 Emissions during 2000:2022

Western Australia vs Average of 8 donor regions Australia

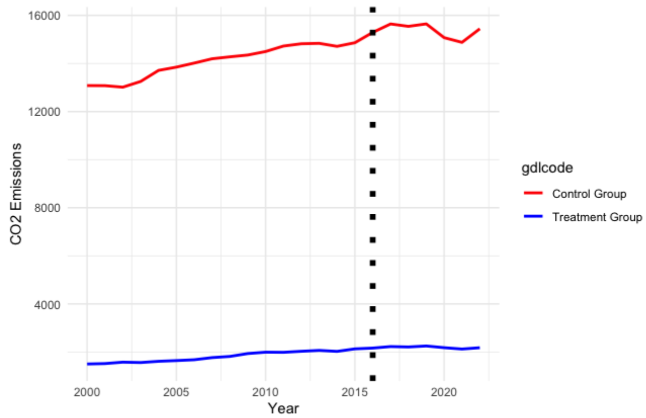


Fig8c. Path plot of CO2 Emissions during 2000:2022

Antofagasta vs Average of 13 donor regions Chile

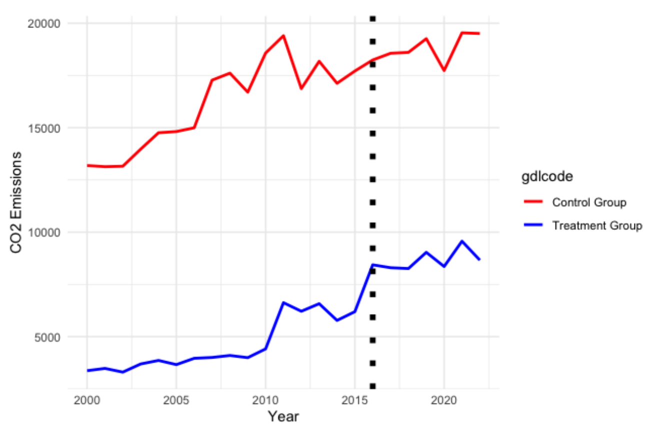
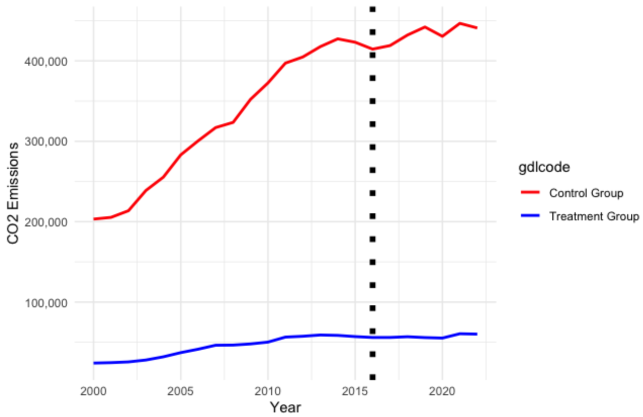


Fig8d. Path plot of CO2 Emissions during 2000:2022

Sichuan vs Average of 31 donor regions China



1.8 PM2.5 Emissions

The trajectory of the second pollutant, PM2.5 (metric tonnes) emissions from both lithium brine and hard-rock mining in Argentina, Australia, Chile, and China, compared to each control average, is depicted in **Figure 9a-d** below. Again, in the pre-treatment period (2000-2015), PM2.5 emissions in both the mining and control group regions, follow a somewhat similar trend, although the trend is considerably more stable in the mining regions. This is particularly the case for Western Australia, Antofagasta (Chile), and Sichuan (China). NOA (Argentina), however, experiences larger differences in PM2.5 emissions over the sample period, with a more comparable trend to its control group.

Fig9a. Path plot of PM2.5 Emissions during 2000:2022

NOA vs Average of 6 donor regions Argentina

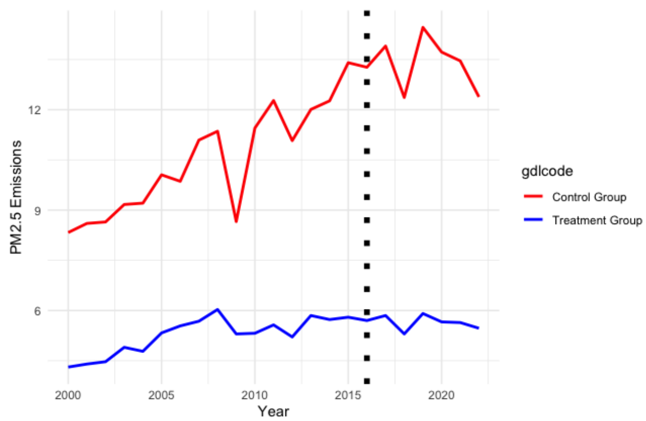


Fig9b. Path plot of PM2.5 Emissions during 2000:2022

Western Australia vs Average of 8 regions in Australia

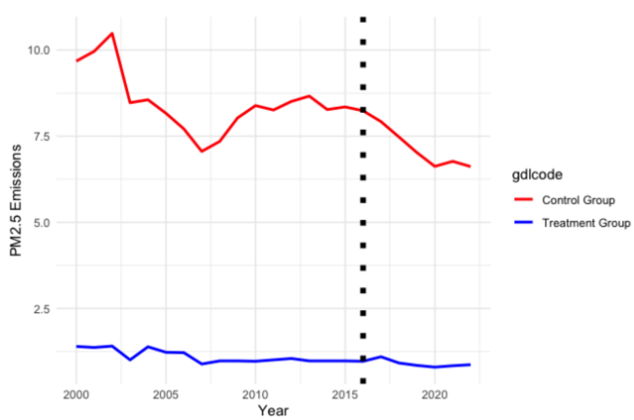


Fig9c. Path plot of PM2.5 Emissions during 2000:2022

Antofagasta vs Average of 13 donor regions Chile

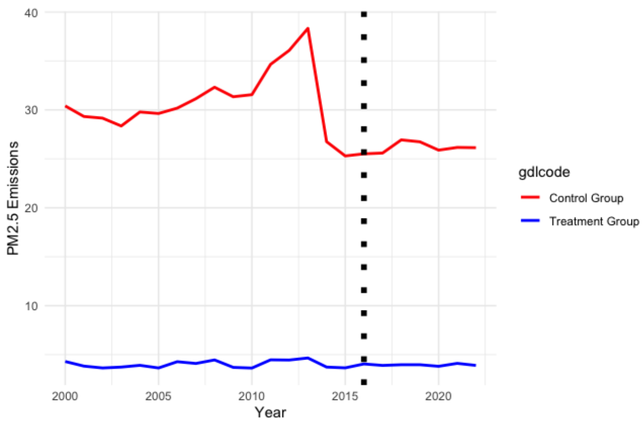
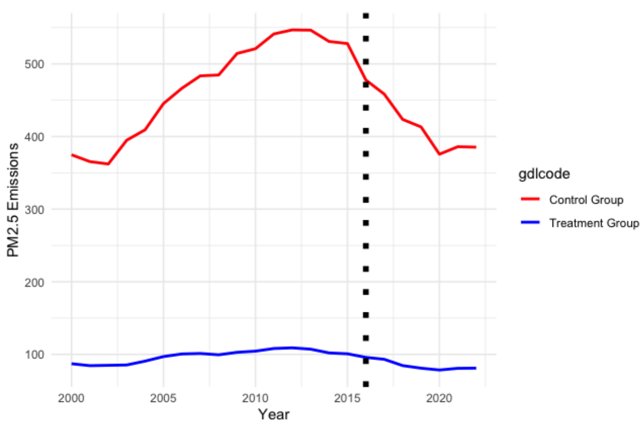


Fig9d. Path plot of PM2.5 Emissions during 2000:2022

Sichuan vs Average of 31 donor regions China



Although a statistical[9] analysis indicates that, on average, the trend in CO_2 and PM2.5 emissions in each of the lithium mining regions is not significantly different from the trend in the donor pool of regions, there is still a concern that unobserved baseline differences may exist between the

[9] Linear regression results yield an insignificant coefficient for the interaction term between a treatment dummy and a pre-intervention period dummy

treated and control groups before the implementation of the Paris Agreement (Kreif et al., 2016). The use of a synthetic control method is particularly valuable in accounting for these pre-treatment dynamics and other complexities, ensuring the isolation of the effect of the intervention (Li, 2020).

1.9 Synthetic Control Group Method Results

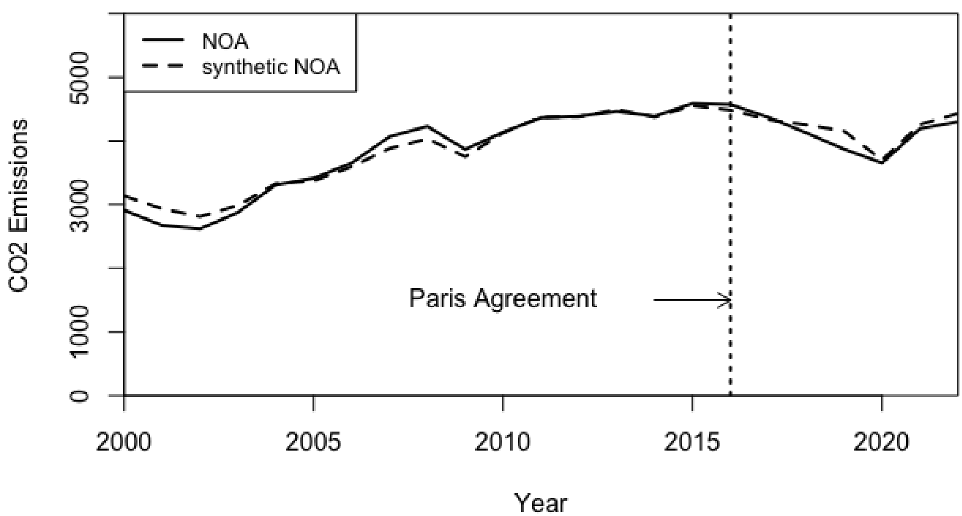
With the use of a synthetic control method, ideally, the synthetic unit should track CO2 and PM2.5 emissions from lithium mining in the treatment group prior to the intervention, and reproduce the values of the key predictors. If successful, it provides a credible counterfactual for the changes in CO2 and PM2.5 emissions caused by the Paris Agreement (Andersson, 2019). In the post-treatment period, the synthetic control unit is then compared to the treated unit, in order to assess the impact of the intervention (Andersson, 2019).

1.9.1 CO2 Emissions

Figures 10a-d below, depict that prior to the implementation of the Paris Agreement in 2016, CO2 emissions from both lithium brine and hard-rock mining within the regions of Argentina, Australia, and China, and their synthetic counterparts, track each other quite closely, apart from Antofagasta (Chile). While the treated and synthetic control units in Chile initially track each other closely, they experience an increasing divergence from the period 2008.

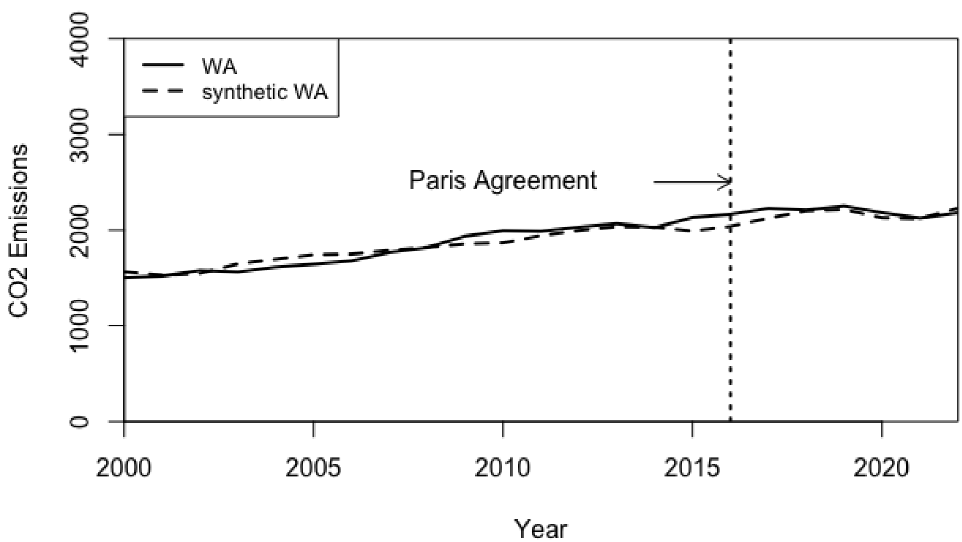
NOA (Argentina) and its synthetic counterpart, which experienced a slight divergence around the periods 2000 to 2004 and 2008, track each other closely, with an average absolute pre-treatment difference of 7.88 metric tonnes in CO2, compared to the pre-treatment regional average of 3,796 metric tonnes. **Appendix B, Table 1a** compares the predictor values for NOA prior to 2016, with the predictor values of synthetic NOA. For the main predictor HDI, NOA and its synthetic counterpart have identical values, with a better fit compared to the sample mean (Andersson, 2019). Additionally, the weights (W) of the five regions in the donor pool are outlined in **Appendix B, Table 2a**. These show that regions NEA (0.441), Cuyo (0.023), and Patagonia (0.515) contribute largely to the creation of a synthetic NOA. These weights attributed to each of the three regions make sense given Argentina's main products, gold, silver, lead, zinc, and lithium, are mined in these areas, such as San Juan (Cuyo), Santa Cruz (Patagonia), and Catamarca, Salta, and Jujuy (which are the lithium mining and processing locations within the NOA region), and therefore may exhibit similar historical CO2 levels (Moore, 2022). Furthermore, the larger weights attributed to both NEA and Patagonia may be due to similar developmental levels. More specifically, NEA experiences a similar infrastructural development level to NOA (Niembro & Sarmiento, 2021), while Patagonia experiences similar levels in HDI.

Fig10a. Path plot of CO2 Emissions from mining during 2000:2022
NOA vs Synthetic NOA



Similar to the trajectory divergences seen between NOA and synthetic NOA, Western Australia and its synthetic counterpart track each other closely, although experiencing an expanding divergence from 2014 onwards, indicating the potential of anticipatory effects. Overall, Western Australia experiences a pre-treatment average absolute difference of 3.78 metric tons in CO2 emissions from its synthetic counterpart. Compared to the pre-treatment regional average of 1,825 metric tonnes of CO2. Additionally, although the HDI predictor values for Western Australia and its synthetic unit are not identical, they are very similar, as outlined in **Appendix B, Table 1b**. The weights (W), as reported in **Appendix B, Table 2b**, show that CO2 emissions from lithium mining in Western Australia are best reproduced by the Northern Territory (0.847). This makes logical sense given its proximity to Western Australia and its similar dry and hot environment, according to the Australian Bureau of Metrology, (2018). Moreover, large parts of the Northern Territory remain uninhabited, much like the sparsely populated nature of Western Australia (Royal Berglee, 2016).

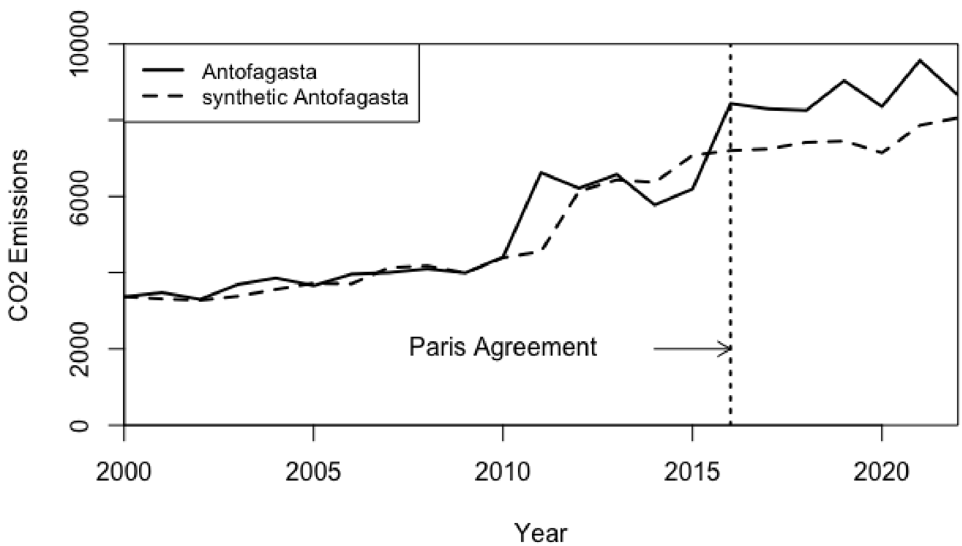
Fig10b. Path plot of CO2 Emissions from mining during 2000:2022
Western Australia vs Synthetic Western Australia



Although Antofagasta (Chile) experienced similar divergences with its synthetic counterpart in 2008, as seen in the other lithium mining regions, this difference did not diminish but rather started to increase. Furthermore, around 2015, this divergence increased further before the intervention of the Paris Agreement, again indicating anticipatory effects. This is reflected in an average absolute difference of 28.22 metric tons of CO2, a difference which although seems quite large compared to NOA and Western Australia, is not particularly dramatic given Antofagasta's pre-treatment CO2 emissions average of 32,055 metric tonnes. **Appendix B, Table 1c,** outlines the values of the key predictors for Antofagasta and its synthetic unit, where the values for HDI and CO2_lag are not identical but rather similar. Moreover, the weights (W) in **Appendix B, Table 2c**, show that Atacama (0.569) has the largest influence on the creation of synthetic Antofagasta. This makes sense as the mines are located in the Salar de Atacama, despite operating in the Antofagasta region (Berg & Sady-Kennedy, 2021).

Fig10c. Path plot of CO2 Emissions from mining during 2000:2022

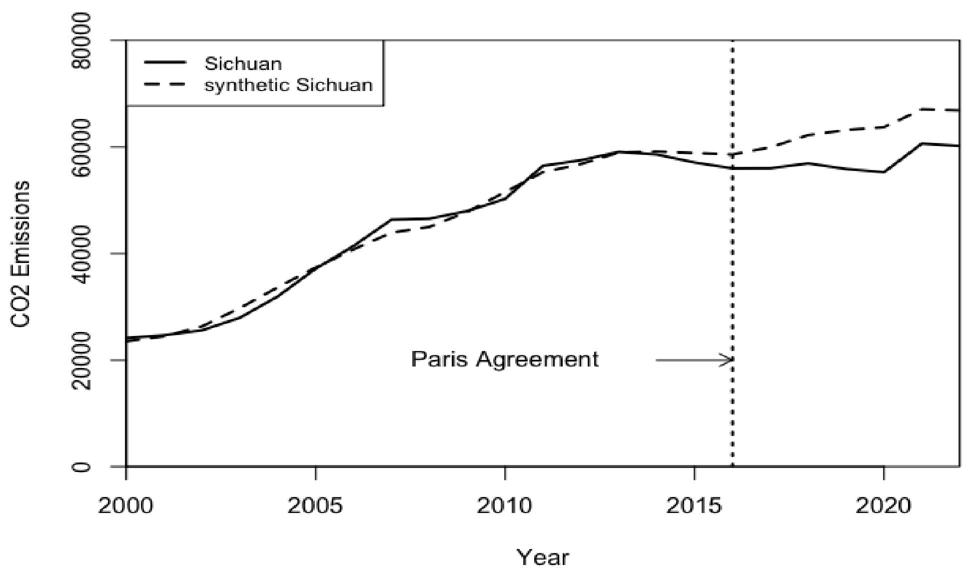
Antofagasta vs Synthetic Antofagasta



CO2 emissions from hard-rock lithium mining in the Sichuan province of China, tend to follow a relatively similar trend to that of its synthetic counterpart, experiencing slight deviations around the periods of 2005 and 2008. Similarly to Western Australia and Antofagasta (Chile), this divergence increases from 2014, resulting in a pre-treatment average absolute difference of 654 metric tonnes. Although this result is not particularly surprising given Sichuan's pre-treatment CO2 average of 44,034 metric tonnes, the difference is quite substantial when considering the difference exhibited between Antofagasta and its synthetic counterpart, which has a somewhat similar CO2 emissions average. **Appendix B, Table 1d**, highlights identical values for the key predictor HDI, between Sichuan and its synthetic counterpart, and a relatively small difference in values for the additional predictors. Furthermore, **Appendix B, Table 2d** indicates that the regions of Heilongjiang (0.366) and Qinghai (0.391) contribute the largest weight to the creation of Sichuan's synthetic counterpart. Heilongjiang is a longstanding industrial mining region and has been notoriously responsible for a significant proportion of China's CO2 emissions, as noted by (Liu &

Li, 2021). Qinghai and Sichuan, border each other and are both located on the Tibetan Plateau, therefore sharing very similar landscapes, resulting in similar environments and climatic conditions to Sichuan (Ma et al., 2022).

Fig10d. Path plot of CO2 Emissions from mining during 2000:2022
Sichuan vs Synthetic Sichuan

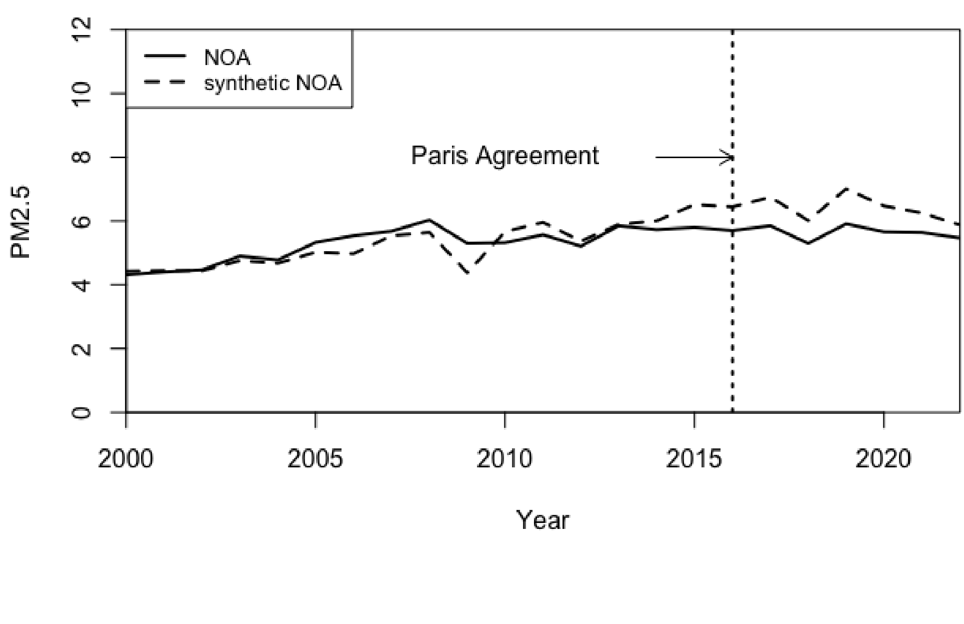


1.9.2 PM2.5 Emissions

In the figures below (**Figure11a-d),** similar to the results observed for CO2 emissions, PM2.5 emissions in Western Australia and Sichuan (China) and their synthetic counterparts track each other closely prior to the implementation of the Paris Agreement in 2016. However, PM2.5 emissions from lithium brine mining in NOA (Argentina) and Antofagasta (Chile) show greater divergence from their corresponding synthetic units, although Antofagasta exhibits less divergence compared to its CO2 emissions trajectory.

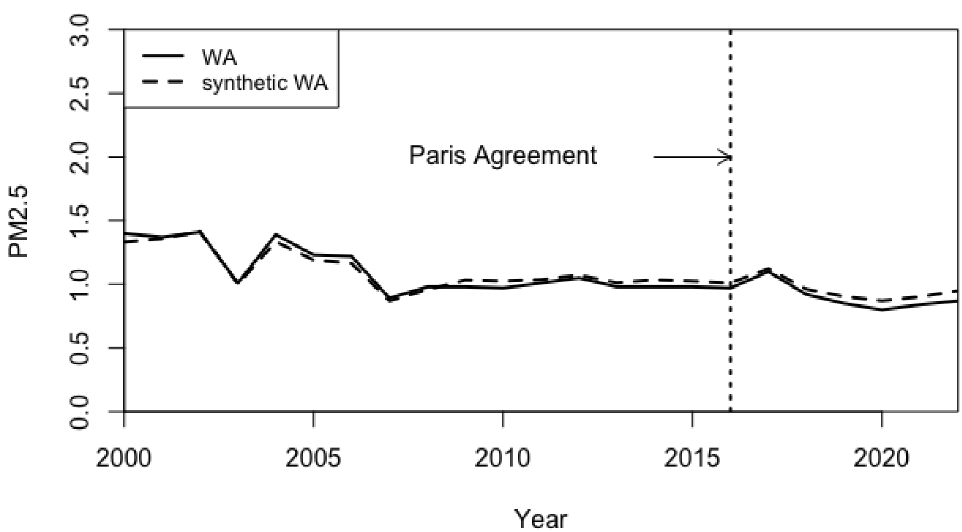
In examining NOA (Argentina), which exhibits a notable difference in regard to its synthetic counterpart, has a pre-treatment average absolute difference of 0.306 metric tonnes of PM2.5 emissions, compared to the region’s pre-treatment average of 5.29 metric tonnes. The most significant discrepancy in trends occurred around 2008, correlating with the presence of the financial crisis (Elliott, 2011). Additionally, for PM2.5, the divergence in trends further increased prior to 2016, given the operation of Argentina's second-largest lithium mine, the Sales de Jujuy project or the Olzaroz Lithium facility, which initially started operating in 2015 (Marchegiani et al., n.d.). **Appendix B, Table 3a**, which compares the values of key predictors for NOA with those for its synthetic counterpart, shows that precipitation, a key predictor, exhibits very similar values while other predictors, including humidity display slightly diverging values. The contributing weights (W) of different regions in Argentina to the creation of synthetic NOA, are highlighted in **Appendix B, Table 4a**, indicating that similar to CO2 emissions, the Cuyo region in Argentina contributes a major weight (0.894) to the creation of synthetic NOA. This is due to its proximity to lithium brine mining and processing sites and its extremely similar arid climate. Both of which are significant determinants of PM2.5 emissions (Federico et al., 2018).

Fig11a. Path plot of PM2.5 Emissions from mining during 2000:2022
NOA vs Synthetic NOA



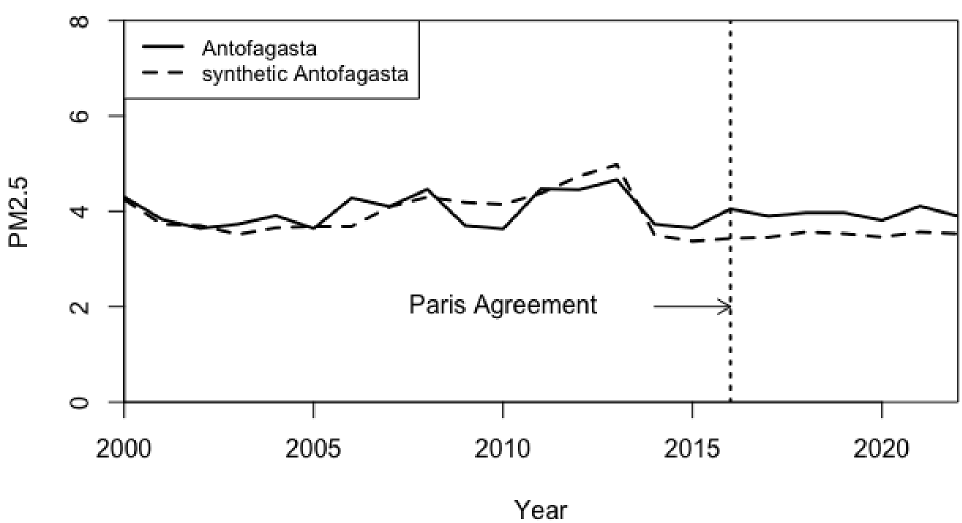
The extremely closely matched trajectory between Western Australia and its synthetic counterpart is illustrated by the very close alignment of the two lines in **Figure 11b**. They experience an average absolute pre-treatment difference of only 0.0359 metric tons of PM2.5 emissions, compared to Western Australia's pre-treatment average of 1.11 metric tonnes. Furthermore, **Appendix B, Table 3b** compares the values of the key predictors for Western Australia prior to 2016 with the same values for synthetic Western Australia. For all predictors, except humidity, Western Australia and its synthetic counterpart have almost identical values, with a much better fit compared to the sample means (Andersson, 2019). South Australia contributes a large weight of 0.662. South Australia is not only situated on the border of Western Australia but is also in close proximity to both Greenbushes and Mount Marion lithium mines (Overview, n.d.; Rani, 2023) **(Appendix B, Table 4b)**.

Fig11b. Path plot of PM2.5 Emissions from mining during 2000:2022
Western Australia vs Synthetic Western Australia



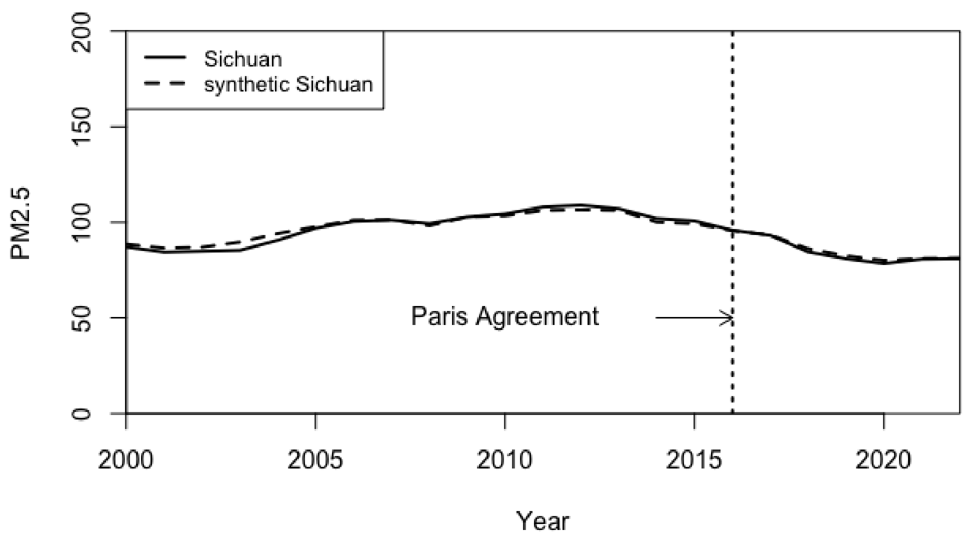
Antofagasta (Chile) experiences very similar divergences in PM2.5 emissions to its synthetic counterpart, with an average absolute difference of only 0.228 metric tonnes, compared to the pre-treatment average of 12.2 metric tonnes. For all key predictors except humidity, Antofagasta and synthetic Antofagasta have very similar values and a better fit compared to their sample means (Andersson, 2019) **(Appendix B, Table 3c)**. The region of Atacama contributes the majority of weight (W = 0.897) to the creation of synthetic Antofagasta, due to its location near the brine mining operations in the Salar de Atacama, as well as its very similar arid nature (Berg & Sady-Kennedy, 2021) **(Appendix B, Table 4c)**.

Fig11c. Path plot of PM2.5 Emissions from mining during 2000:2022
Antofagasta vs Synthetic Antofagasta



Similarly, **Figure 11d** illustrates a near-perfect alignment between Sichuan and synthetic Sichuan. However, despite this close tracking, the higher level of PM2.5 emissions in China results in an average absolute difference of 1.585 metric tons of PM2.5. This difference is quite small considering Sichuan's average of 97.7 metric tonnes between 2000 and 2016. Sichuan and synthetic Sichuan have identical values for precipitation, and very similar values for humidity, and other predictors. Each of the predictor values exhibits a better fit compared to their sample means (Andersson, 2019) **(Appendix B, Table 3d)**. The Guizhou region of China contributes the largest weight (0.585), with Heilongjiang contributing a smaller weight (0.180), to the construction of the synthetic control **(Appendix B, Table 4d)**. Guizhou, which borders Sichuan, experiences a similar concentration of precipitation (Shi & Zhang, 2023).

Fig11d. Path plot of PM2.5 Emissions from mining during 2000:2022
Sichuan vs Synthetic Sichuan



1.10 Changes in Emissions

The post-treatment distance between each treatment and synthetic control unit, as illustrated in **Figures 10 and 11** measures the impact of the Paris Agreement on CO2 and PM2.5 emissions due to increased lithium mining, driven by the demand for electric vehicles (Andersson, 2019; Ciftci & Lemaire, 2023). This distance is further illustrated in the gap plots in **Appendix B, Figures 1 and 2.**

Focusing first on lithium brine mining in the South American lithium triangle, CO2 emissions in NOA (Argentina) were 86.7 metric tonnes higher in 2016 than they would have been, had the Paris Agreement not occurred. However, the presence of the intervention created a gradual decrease in CO2 emissions (Andersson, 2019), over the post-treatment period as CO2 emissions were 129.8 lower in 2022, than they would have been in the absence of the Paris Agreement, providing a cumulative reduction of 527 metric tons in the period 2016-2022. Furthermore, despite exhibiting a cumulative reduction in PM2.5 emissions of 5.3 metric tonnes, these emissions were reduced by a small amount of 0.33665 metric tonnes, from -0.744 in 2016 to -0.4075 in 2022, relative to a situation in the absence of the Paris Agreement. Indicating the gradual increase in PM2.5 emissions over the post-treatment period (Andersson, 2019). In contrast, CO2 emissions in Antofagasta (Chile) were 1,853 metric tons higher in 2016, than they would have been in the absence of the Paris Agreement. Although the rate of this increase became more gradual over the post-treatment period (Andersson, 2019), Antofagasta experienced a cumulative increase of 12,924 metric tonnes over the period 2016-2022. Similarly, PM2.5 emissions in Antofagasta were 0.622 metric tonnes higher in 2016 than they would have been, compared to a situation where the Paris Agreement had not occurred, with a cumulative increase of 3.16 metric tonnes from the period 2016-2022.

Moving onto hard-rock lithium mining, CO2 emissions in Western Australia were 125 metric tonnes higher in 2016, relative to a situation in the absence of the Paris Agreement. Again, while the rate at which CO2 emissions increased, diminished over the post-treatment period (Andersson, 2019), Western Australia exhibited a total or cumulative increase of 284.7 metric tonnes. PM2.5 emissions in Western Australia, on the other hand, were largely stable throughout the post-treatment period, decreasing slightly from -0.041 metric tonnes in 2016 to -0.077 metric tons in 2022, providing a cumulative increase of 39.5 in the post-treatment period. In Sichuan, where hard-rock lithium mining is also employed, C02 emissions were 2,595 metric tonnes lower in 2016, compared to a scenario without the Paris Agreement. This dramatic reduction provided a cumulative decrease of 40,661 metric tonnes. Furthermore, PM2.5 emissions were 0.262 metric tonnes lower in 2016, exhibiting a cumulative decrease of 10.6 metric tonnes over the post-treatment period.

1.11 Placebo tests

1.11.1.1 In-Time Placebo Test

To further validate the results two placebo tests were conducted. Firstly, an in-time placebo test was performed to ensure that the changes in emissions previously observed were indeed due to the Paris Agreement and not other factors. In conducting the in-time placebo test, the period of intervention is shifted from the period 2016 to 2011, which is the midpoint of the entire sample period. The goal of the in-time placebo test is to confirm that the placebo does not cause a large divergence in emissions between the mining regions and their synthetic counterparts. If a large placebo effect is observed, it would raise doubts about whether the observed results are genuinely due to the intervention of the Paris Agreement (Andersson, 2019). **Figures 3a-d in Appendix C** show no such divergence in the analysis of CO2 emissions. Therefore, leading to the conclusion that any changes in CO2 emissions in the four mining regions are indeed due to the intervention of the Paris Agreement. Secondly, considering the in-time placebo test for PM2.5 emissions in **Appendix C, figures 4a-d** indicate that similarly to the in-time placebo test for CO2 emissions, the mining regions of NOA (Argentina), Western Australia, Antofagasta (Chile), and Sichuan (China), along with their synthetic counterparts, experienced no divergence from their original path plots in **figures 11a-d.** Indicating the robustness of all the previously established results, reinforcing that the observed effects are due to the intervention and not due to other confounding factors.

1.11.1.2 In-Space Placebo Test

For the in-space placebo test, the treatment is applied to each different region in the donor pool one at a time, using the synthetic control method to construct a synthetic counterpart for each of these regions. This allows for the comparison of results found for each of the mining regions to the results of the donor regions. If the trend in both CO2 and PM2.5 emissions in the mining regions differs from the donor pool regions, it indicates that the effect of intervention appears to be specific to the treated unit. This strengthens the validity of the results and suggests that the Paris Agreement impacted CO2 and PM2.5 emissions, in the major lithium mining regions (Gilchrist et al., 2023).

This method determines if the results obtained for each major lithium mining region are unusually large by comparing them to the placebo results for all regions in the donor pool. More specifically, this method allows for the computation of the ratio of post-treatment to pre-treatment Mean Squared Prediction Errors (MSPEs) for the treated units compared to each control unit (Abadie et al., 2010). This ratio test then allows for the calculation of p-values, measured as the fraction of regions in the control group with an MSPE ratio equal to or larger than that of the treated regions. This measures the probability of finding an MSPE ratio as large as the treated unit’s ratio by chance (Andersson, 2019).

To illustrate the in-space placebo tests, **Figures 5 and 6** in **Appendix C** show the gap plots for CO2 and PM2.5 emissions for the mining regions compared to each of the control groups when assigned as the treated unit. In NOA (Argentina), CO2 emissions from the “actual” treated unit remained steady over the sample period and did not increase or decrease in a way that stood out or differed from any of the placebo units. Similarly, for PM2.5 emissions, the “actual”, just like the placebo units, followed the same stable trend over the sample period. Indicating the invalidation of results as the effect of the intervention may not be specific to NOA.

In Western Australia, CO2 emissions increased steadily during the pre-treatment period until 2016, after which they increased suddenly, and then continued to increase steadily throughout the post-treatment period, as illustrated in **Appendix C, Figure 5b.** This trend is in contrast to the placebo units, which remained stable over the sample period. PM2.5 emissions in the "actual" treatment group remained stable over the sample period, while PM2.5 emissions in the placebo units exhibited substantial volatility. This effect indicates that CO2 emissions from lithium mining in Western Australia increased in response to the Paris Agreement, while PM2.5 emissions remained relatively stable, exhibiting a minor decrease. The in-space placebo test validates that this effect is specific to the "actual" treatment group. The increase in CO2 emissions in Western Australia in response to the Paris Agreement is consistent with existing literature (Harvest, 2024; hpprocess, 2023), which explains the energy-intensive process of lithium spodumene mining, particularly in blasting and drilling processes, which are followed by the heating and cooling of ore to remove impurities. Each of these contributes to the release of greenhouse gas (GHG) emissions, particularly in the form of CO2 (Koščová et al., 2018). However, these effects, although validated, are not statistically significant, with p-values of 0.50 and 0.33, respectively.

As for CO2 emissions in Antofagasta (Chile) and the control units (once attributed to treated units), seem to experience opposing trends throughout the sample period, CO2 emissions in the “actual” treated unit increased in response to what was likely the anticipation of the Paris Agreement in 2014, exhibiting a substantially different trend from the placebo units over the sample period. Similarly to the results for Western Australia, PM2.5 emissions in Antofagasta remained stable across the sample period, although experiencing a slight increase in the post-treatment period, while the placebo units experienced much more volatility. In general, these results indicate that CO2 emissions from lithium mining have increased in anticipation of the Paris Agreement. Furthermore, these results are robust, as they are specific to the “actual” treated unit.

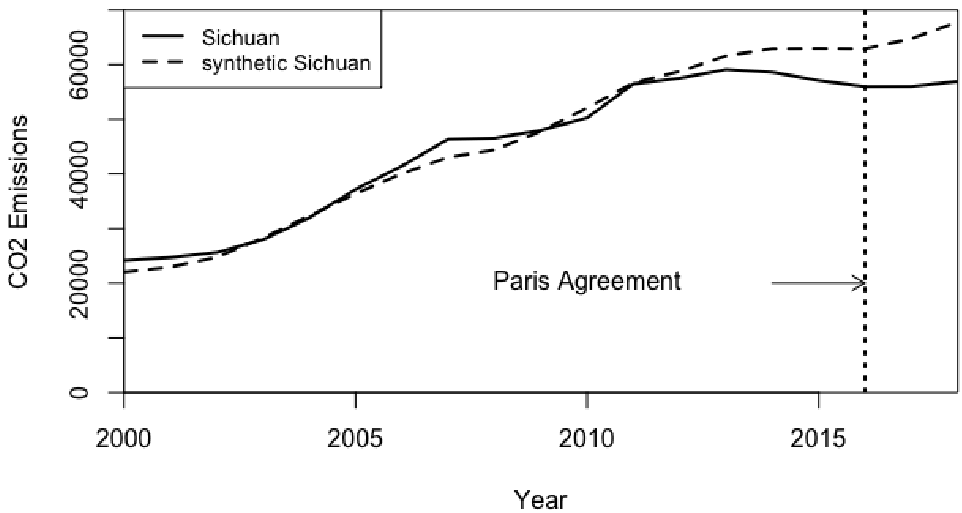
This increase in CO_2 emissions is insignificant with a p-value of 0.923, meaning that the effect observed, is not statistically different from what could be expected at random, as is the slight decrease in PM2.5 emissions, with a p-value of 0.5. These results are however consistent with the expectation that CO_2 emissions from lithium brine mining arise from the high power requirement of machinery used to pump the brine and freshwater from the Salar into different ponds, despite the use of solar concentration (Mas-Fons et al., 2024).

Sichuan (China) experiences relative stability in both CO_2 and PM2.5 emissions over the sample period, while in both cases the placebo units exhibit much more volatility over the same period, as illustrated in **Figures 5d and 6d.** Although the emissions in response to the Paris Agreement are not statistically different from what could be expected by chance (with p-values of 0.645 and 0.7301, respectively), CO_2 emissions in Sichuan reduced in response to the Paris Agreement, while PM2.5 emissions have for the most part remained the same. Although the COVID-19 crisis affected production in all countries, the effects may have been more pronounced in China due to its widespread shutdown in the first few months of the crisis and the repeated lockdowns that impacted supply chains well into 2021. Therefore, the larger impact of COVID-19 in China, particularly in the Chinese battery export market, may have substantially affected the production of lithium spodumene. Leading to a large reduction in CO_2 emissions and a smaller reduction in PM2.5 emissions (Dyatkin & Meng, 2020).

1.12 Potential Co-founders

Despite the fact that the Synthetic Control Method (SCM) controls for some potential unobserved confounders, the original sample period from 2000-2022 was adjusted to ensure that the previously established results for CO_2 and PM2.5 emissions, in the mining regions of Argentina, Australia, Chile, and China, are in-fact due to the Paris Agreement and not the prolonged effects of COVID-19 crisis, which impacted lithium production levels (Albalate et al., 2021). Although the COVID-19 crisis was global in nature (Dyatkin & Meng, 2020), the previously specified and robust results for the mining regions of Anfogasta (Chile) and Western Australia exhibited a cumulative increase in emissions over the post-treatment period and were therefore in line with expectations, while CO_2 emissions in Sichuan (China) decreased substantially in the post-treatment period. In order to ensure that the previously established effects have not been driven by this period, the years 2019-2022, during which the COVID-19 crisis may have impacted both emissions were excluded.

Fig12a. Path plot of CO2 Emissions from mining during 2000:2018
Sichuan vs Synthetic Sichuan



Based on the results of the Synthetic Control Method (SCM) illustrated in **Figure 12a**, the analysis for Sichuan (China) from 2000 to 2018, excluding the years affected by the COVID-19 crisis, indicate that the COVID-19 pandemic did indeed have an impact on the release of CO2 emissions from lithium mining. More specifically, in the post-treatment period, CO2 emissions in 2016 initially decreased by 2,595 metric tonnes, compared to a situation in the absence of the Paris Agreement, when using the full sample (2000-2022). However, when the years 2019-2022 were excluded, there was a decrease in CO2 emissions of 6,919 metric tonnes. This substantial difference suggests that the reduction in emissions observed in the full sample may have been influenced by the COVID-19 crisis rather than the Paris Agreement. Further supporting this conclusion, the path plot in **Figure 12a** illustrates that CO2 emissions in China started to decrease around 2011. In contrast, under the full sample, the path plot indicated that this reduction began around 2014. The increased discrepancy in the trajectory between Sichuan and its synthetic counterpart in the pre-treatment period, under the adjusted sample, highlights the potential confounding effect of the

COVID-19 crisis, which caused significant disruptions in industrial activity and production levels, in the lithium mining region of Sichuan (China) (Andersson, 2019; Dyatkin & Meng, 2020).

Although the reduction of CO2 emissions in Sichuan is driven by the presence of the COVID-19 pandemic, PM2.5 emissions in this region, on the other hand, experienced no divergence in its trajectory from the original sample period, (**Appendix C Fig8c**) Similarly, the results for CO2 and PM2.5 emissions in Antofagasta (Chile) and Western Australia, are robust to the consideration of the COVID-19 crisis, as the trajectory of emissions over the adjusted sample period were identical to the trajectory over the original sample period, as illustrated in **Appendix C, Figures 7 and 8.**

1.13 Data and Analysis limitations

Although this thesis paper pioneers investigation into the underexplored effects of lithium mining, in repose to the implementation of the Paris Agreement and its policy counterparts, the unfamiliarity of this topic presents significant data limitations. Despite the availability of both subnational CO2 and PM2.5 emissions data, obtaining this data at the mine level would have increased the accuracy of the results obtained, and therefore provided a more realistic quantification of these highly debated effects. Furthermore, the synthetic control method utilizes the inclusion of a range of key predictors, in order to maximize the pre-treatment similarity between the treatment and synthetic control group (Andersson, 2019). The lack of data available to include as predictor variables, particularly concerning CO2 emissions, may suggest that the results obtained may not be entirely due to the invention itself.

Regarding analytical limitations, several factors are presented given the research time period and the use of the synthetic control method (SCM), as an analytical tool in this research. Despite the ambitious attempts to investigate the impact of lithium mining on a wide range of environmental indicators, the extent of analysis required surpassed the time period available, hindering the depth of this analysis. In terms of the chosen analytical method, a significant constraint arose from the fact that the synthetic control method is typically applied to a single treated unit and is less effective when applied to multiple treated units (Kreif et al., 2016). As a result, the analysis was segmented not only into separate assessments for each environmental impact variable but also for each of the four lithium-mining regions. This approach limited the comprehensibility of results. A second and significant issue regarding the choice of the statistical method employed relates to the fact that analysis under the synthetic control method is based on the assumption of a linear relationship between the outcome and predictor variables. Any potential presence of non-linearity is argued to generate biased estimates (Engelbrektson, n.d.). Therefore, while under the assumption of linearity, the synthetic control method controls for heterogeneity between the treated and control units, as embedded in the method itself, the absence of linearity provides a risk that unobserved factors impact the outcome differently in the treatment and control groups (Engelbrektson, n.d.). Furthermore, the nature of the Paris Agreement as a policy may not have been particularly suited for the synthetic control method of analysis, as the implementation of the Paris Agreement has been gradual and varied across different countries, and often accompanied by subordinated policies. This dynamic and complex nature of the Paris Agreement is reflected in the potential anticipatory effects previously established. Meaning the analysis of such a policy intervention may have been better suited to a different form of analysis (Dimitrov, 2016).

V. Conclusion

The Paris Agreement has largely impacted the transport sector, reducing transport emissions through the adoption of electric vehicles (EVs)(McKay, 2023). The unprecedented demand for lithium-ion batteries used in EVs has initiated a corresponding increase in the demand for lithium minerals, met primarily through the expansion of mining operations (Ciftci & Lemaire, 2023). In order to properly assess whether the decarbonization of the transport sector is in fact “clean”, and therefore to support public policy intentions, it is crucial to understand how both CO2 and PM2.5 emissions have changed in the lithium mining regions, as a result of the Paris Agreement.

The empirical findings suggest that CO2 emissions increased in anticipation of the Paris Agreement, in order to meet the growing global demand for EVs. This is particularly the case for lithium brine mining in Antofagasta (Chile), where CO2 emissions increased by a total of 12,924 metric tonnes, and hard-rock lithium mining in Western Australia, where CO2 emissions increased by 284.7 metric tonnes in the period 2016-2022. These findings support popular argumentation regarding the adverse environmental impacts of the expansion of lithium mining, in the regions within which the extraction occurs (Koščová et al., 2018; Mas-Fons et al., 2024). While these papers argue that the increased emissions mainly occur in the form of CO2, Koščová et al., (2018) further argue that PM2.5 emissions, although secondary to CO2 emissions, have increased in response to the expansion of lithium mining. The results established for PM2.5 indicate that these emissions remained relatively stable, exhibiting a slight increase in Antofagasta (Chile) and a decrease in Western Australia, in response to the Paris Agreement. Highlighting the importance of the increased CO2 emissions as a result of the policy-driven push to decarbonize the transport sector (Koščová et al., 2018), and potentially indicating the effectiveness of dust suppression measures in the process of blasting and excavating for lithium-bearing ore (Rock, 2023).

However, given the presence of the COVID-19 crisis within the sample period, and its particular impact on the battery sector in China (Dyatkin & Meng, 2020), the results for CO2 and PM2.5 emissions, from lithium mining in Sichuan, cannot with certainty be credited to the Paris Agreement but rather the reduction in lithium production. Although the COVID-19 pandemic was not specific to China, inducing reductions in lithium production globally, the effects may have been more pronounced due to its widespread lockdown in the first few months of the crisis and the then repeated lockdowns, particularly damaging the domestic export market (Dyatkin & Meng, 2020). In general, causing a substantial cumulative decrease in emissions, rather than a periodical one.

Nevertheless, contrary to Harvest, (2024), where it is argued that hard-rock lithium mining for spodumene is three times more carbon-intensive than lithium brine mining, a series of back-of-the-envelope calculations measure the CO2 intensity per metric tonne of lithium produced in the two forms of extraction, before the COVID-19 pandemic. In 2018 in Western Australia, emissions increased by 10.7 metric tonnes, while producing a total of about 313,000 metric tonnes of lithium (USGS, 2018), meaning that in 2018 Western Australia experienced an increase of 0.00003195 metric tonnes of CO2 per tonne of lithium produced. In Antofagasta (Chile), CO2 emissions increased by 1545 metric tonnes in 2018, when total lithium production amounted to about 87,029 metric tonnes (Cabello, 2021). Leading to an increase of 0.0178 metric tonnes of CO2 per metric tonne of lithium produced. In general, these calculations suggest that lithium mining in Antofagasta, which utilizes a form of lithium brine mining, is more energy-intensive per tonne of lithium produced, than hard-rock lithium mining, despite its more visually impactful nature (Filipenco, 2023; Lorca et al., 2022).

It is important to note that this thesis paper does not oppose the use of lithium as a key material required in the energy transition (Ghorbani et al., 2024), but rather this paper aims to provide statistical evidence regarding the negative effects that lithium mining, both in the form of brine as well as hard-rock mining, has on the local environments in which the mining process takes place, particularly in terms of the release of CO2 and PM2.5 emissions. The investigation of such impacts allows for a more accurate perception of the so-called "clean" transition to EVs. Furthermore, although the research shed light on new suggestive evidence regarding the sustainability of decarbonizing the transport sector, there is significant room for future research. First and foremost, building on the data and analytical limitations previously discussed. Furthermore, considering the complete turnover of combustion vehicles to EVs, this is a topic that will be extremely insightful to re-investigate in the next decade and a half. Additionally, investigating this relationship between lithium mining in response to the Paris Agreement, which induced an unprecedented demand for EVs, and its adverse environmental impacts, may become increasingly important given the potential geopolitical shift regarding the Global North's reliance on Chinese-produced lithium-ion batteries.

References

Abadie, A., Diamond, A., & Hainmueller, J. (2010). Synthetic Control Methods for Comparative Case Studies: Estimating the Effect of California's Tobacco Control Program. Journal of the American Statistical Association, 105(490), 493–505. https://doi.org/10.1198/jasa.2009.ap08746

Abadie, A., Diamond, A., & Hainmueller, J. (2015). Comparative Politics and the Synthetic Control Method: COMPARATIVE POLITICS AND THE SYNTHETIC CONTROL METHOD. American Journal of Political Science, 59(2), 495–510. https://doi.org/10.1111/ajps.12116

Abadie, A., & Vives-i-Bastida, J. (n.d.). Synthetic Controls in Action.

Acemoglu, D., Johnson, S., Kermani, A., Kwak, J., & Mitton, T. (2016). The value of connections in turbulent times: Evidence from the United States. Journal of Financial Economics, 121(2), 368–391. https://doi.org/10.1016/j.jfineco.2015.10.001

Agusdinata, D. B., Liu, W., Eakin, H., & Romero, H. (2018). Socio-environmental impacts of lithium mineral extraction: Towards a research agenda. Environmental Research Letters, 13(12), 123001. https://doi.org/10.1088/1748-9326/aae9b1

Albalate, D., Bel, G., & Mazaira, F. A. (2021). Decoupling synthetic control methods to ensure stability, accuracy and meaningfulness. SERIEs, 12. https://doi.org/10.1007/s13209-021-00242-8

Altiparmak, S. O. (2023). China and Lithium Geopolitics in a Changing Global Market. Chinese Political Science Review, 8(3), 487–506. https://doi.org/10.1007/s41111-022-00227-3

Andersson, J. J. (2019). Carbon Taxes and CO2 Emissions: Sweden as a Case Study. American Economic Journal: Economic Policy, 11(4), 1–30. https://doi.org/10.1257/pol.20170144

Ángel, R. (2022, January 26). It is also happening in Argentina: The looting of lithium for transnational interest. El Ciudadano. https://www.elciudadano.com/en/it-is-also-happening-in-argentina-the-looting-of-lithium-for-transnational-interest/01/26/

Ardizzone, J. V. (2023, September 26). NASA Scientific Visualization Studio | GEOS-FP Relative Humidity. NASA Scientific Visualization Studio. https://svs.gsfc.nasa.gov/5150/

Australian Bureau of Metrology. (2018). Why do we have different climates across Australia? - Social Media Blog - Bureau of Meteorology. corporateName=Bureau of Meteorology.

Retrieved June 15, 2024, from https://media.bom.gov.au/social/blog/1837/why-do-we-have-different-climates-across-australia/

Australia Lithium production—Data, chart. (n.d.). TheGlobalEconomy.Com. Retrieved May 16, 2024, from https://www.theglobaleconomy.com/Australia/lithium_production/

Baker, E., Davies, M., Fourie, A., Mudd, G., & Thygesen, K. (n.d.). MINE TAILINGS FACILITIES: OVERVIEW AND INDUSTRY TRENDS.

Barich, A. (2023). Mineral Resources bullish on Wodgina lithium plant expansions in Albemarle JV. Retrieved June 25, 2024, from https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/mineral-resources-bullish-on-wodgina-lithium-plant-expansions-in-albemarle-jv-78053749

Berg, R. C., & Sady-Kennedy, T. A. (2021). South America's Lithium Triangle: Opportunities for the Biden Administration. https://www.csis.org/analysis/south-americas-lithium-triangle-opportunities-biden-administration

Bhutada, G. (2022, December 23). Visualizing 25 Years of Lithium Production, by Country. Elements by Visual Capitalist. https://elements.visualcapitalist.com/25-years-of-lithium-production-by-country/

Bouttell, J., Craig, P., Lewsey, J., Robinson, M., & Popham, F. (2018). Synthetic control methodology as a tool for evaluating population-level health interventions. Journal of Epidemiology and Community Health, 72(8), 673–678. https://doi.org/10.1136/jech-2017-210106

Cabello, J. (2021). Lithium brine production, reserves, resources and exploration in Chile: An updated review. Ore Geology Reviews, 128, 103883. https://doi.org/10.1016/j.oregeorev.2020.103883

Cargill, J. (n.d.). Citizens vs mining. Retrieved May 2, 2024, from https://www.bmartin.cc/dissent/documents/Cargill.html

CDC. (2023). Particle Pollution | Air | CDC. https://www.cdc.gov/air/particulate_matter.html

Chan, R. (2022, November 21). Record Greenbushes production to meet lithium demand. Australian Mining. https://www.australianmining.com.au/record-greenbushes-production-to-meet-lithium-demand/

Ciftci, M. M., & Lemaire, X. (2023). Deciphering the impacts of 'green' energy transition on socio-environmental lithium conflicts: Evidence from Argentina and Chile. The Extractive Industries and Society, 16, 101373. https://doi.org/10.1016/j.exis.2023.101373

Clarke, D., Pailañir, D., Carleton Athey, S., & Imbens, G. W. (2023). Synthetic Difference-in-Differences Estimation. SSRN Electronic Journal. https://doi.org/10.2139/ssrn.4346540

Copernicus Climate Change Service. (2019). ERA5 monthly averaged data on single levels from 1940 to present [dataset]. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). https://doi.org/10.24381/CDS.F17050D7

Costa, L., Rybski, D., & Kropp, J. (2011). A Human Development Framework for CO2 Reductions. PLoS ONE, 6, e29262. https://doi.org/10.1371/journal.pone.0029262

Daly, T. (2020, December 8). Tianqi gets $1.4 billion lithium mine lifeline from Australia's IGO. Reuters. https://www.reuters.com/article/idUSKBN28I2AH/

Denyer, S. (2023, April 12). Tibetans in anguish as Chinese mines pollute their sacred grasslands. Washington Post. https://www.washingtonpost.com/world/asia_pacific/tibetans-in-anguish-as-chinese-mines-pollute-their-sacred-grasslands/2016/12/25/bb6aad06-63bc-11e6-b4d8-33e931b5a26d_story.html

Dimitrov, R. S. (2016). The Paris Agreement on Climate Change: Behind Closed Doors. Global Environmental Politics, 16(3), 1–11. https://doi.org/10.1162/GLEP_a_00361

Dolma, R. (2016, June 6). Lichu River Poisoned—Case of Minyak Lhagang Lithium Mine Protest. Central Tibetan Administration. https://tibet.net/lichu-river-poisoned-case-of-minyak-lhagang-lithium-mine-protest/

Doudchenko, N., & Imbens, G. (2016). Balancing, Regression, Difference-In-Differences and Synthetic Control Methods: A Synthesis (w22791; p. w22791). National Bureau of Economic Research. https://doi.org/10.3386/w22791

Dyatkin, B., & Meng, Y. S. (2020). COVID-19 disrupts battery materials and manufacture supply chains, but outlook remains strong. Mrs Bulletin, 45(9), 700–702. https://doi.org/10.1557/mrs.2020.239

EARTHWORKS. (2020, June 25). Atacama, Chile. Earthworks. https://earthworks.org/blog/atacama-chile-lithium/

EDGAR - The Emissions Database for Global Atmospheric Research. (n.d.). Retrieved April 1, 2024, from https://edgar.jrc.ec.europa.eu/

Elliott, L. (2011, August 7). Global financial crisis: Five key stages 2007-2011. The Guardian. https://www.theguardian.com/business/2011/aug/07/global-financial-crisis-key-stages

Energy, D. (2024, February 20). Lithium Mining Process: An Environmental Point of View. Dragonfly Energy. https://dragonflyenergy.com/understanding-the-lithium-mining-process-from-an-environmental-point-of-view/

Engelbrektson, O. (n.d.). Why Synthetic Control estimators are biased and what to do about it:

European Parliament. (2023). Making batteries more sustainable, more durable and better-performing | News | European Parliament. (2023, June 14). https://www.europarl.europa.eu/news/en/press-room/20230609IPR96210/making-batteries-more-sustainable-more-durable-and-better-performing

Evans, S. (2020, May 11). Drought: How water scarcity could affect mining in Australia. Mining Technology. https://www.mining-technology.com/features/drought-how-water-scarcity-could-affect-mining-in-australia/

Federico, O., Norte, F., & Araneo, D. (2018). A probability index for surface zonda wind occurrence at Mendoza city through vertical sounding principal components analysis. Theoretical and Applied Climatology, 131. https://doi.org/10.1007/s00704-016-1983-7

Fenix Lithium Mine, Salar Del Hombre Muerto—NS Energy. (n.d.). Retrieved March 25, 2024, from https://www.nsenergybusiness.com/projects/fenix-lithium-mine-salar-del-hombre-muerto/

Filipenco, D. (2023). Five major lithium-producing countries in the world. DevelopmentAid. Retrieved June 22, 2024, from https://www.developmentaid.org/news-stream/post/170661/five-major-lithium-producing-countries

Fu, H., Zhang, Y., Liao, C., Mao, L., Wang, Z., & Hong, N. (2020). Investigating PM2.5 responses to other air pollutants and meteorological factors across multiple temporal scales. Scientific Reports, 10(1), 15639. https://doi.org/10.1038/s41598-020-72722-z

Gao, J., Yu, Y., Wang, D., Wang, W., Yu, F., Zhang, S., Wang, C., Dai, H., Hao, X., & Cen, K. (2022). Multielement biogeochemistry and lithium isotopic composition of the dominant plants at the Jiajika mine, western Sichuan, China—The largest hard rock-type lithium mine in Asia. Applied Geochemistry, 136, 105138. https://doi.org/10.1016/j.apgeochem.2021.105138

Gao, T., Fan, N., Chen, W., & Dai, T. (2023). Lithium extraction from hard rock lithium ores (spodumene, lepidolite, zinnwaldite, petalite): Technology, resources, environment and cost. China Geology, 6(1), 137–153. https://doi.org/10.31035/cg2022088

Garcés, I., & Alvarez, G. (2020). WATER MINING AND EXTRACTIVISM OF THE SALAR DE ATACAMA, CHILE (p. 199). https://doi.org/10.2495/EID200181

Ghorbani, Y., Zhang, S., Bourdeau, J., Chipangamate, N., Rose, D., Valodia, I., & Nwaila, G. (2024). The strategic role of lithium in the green energy transition: Towards an OPEC-style framework for Green Energy-Mineral Exporting Countries (GEMEC). Resources Policy, 90, 104737. https://doi.org/10.1016/j.resourpol.2024.104737

Gilchrist, D., Emery, T., Garoupa, N., & Spruk, R. (2023). Synthetic Control Method: A tool for comparative case studies in economic history. Journal of Economic Surveys, 37(2), 409–445. https://doi.org/10.1111/joes.12493

Greenbushes Mine, Greenbushes Tinfield, Bridgetown-Greenbushes Shire, Western Australia, Australia. (n.d.). Retrieved June 15, 2024, from https://www.mindat.org/loc-11514.html

Gu, G., & Gao, T. (2021). Sustainable production of lithium salts extraction from ores in China: Cleaner production assessment. Resources Policy, 74, 102261. https://doi.org/10.1016/j.resourpol.2021.102261

Guo, X., Zhang, J., & Tian, Q. (2021). Modeling the potential impact of future lithium recycling on lithium demand in China: A dynamic SFA approach. Renewable and Sustainable Energy Reviews, 137, 110461. https://doi.org/10.1016/j.rser.2020.110461

Hard rock lithium vs. Brine—How do their carbon curves compare? (2023, March 3). Benchmark Source. https://source.benchmarkminerals.com/article/hard-rock-vs-brine-how-do-their-carbon-curves-compare

Harvest, L. (2024, March 22). Lithium Extraction Methods—Lithium Harvest. Lithiumharvest.Com. https://lithiumharvest.com/knowledge/lithium-extraction/lithium-extraction-methods/

Hausfather, Z. (2018, January 19). Explainer: What climate models tell us about future rainfall.Carbon Brief. https://www.carbonbrief.org/explainer-what-climate-models-tell-us-aboutfuture-rainfall/

Horowitz, C. A. (2016). Paris Agreement. International Legal Materials, 55(4), 740–755. https://doi.org/10.1017/S0020782900004253 hpprocess. (2023, March 15). The Lithium Mining Process. Heyl Patterson. https://www.hpprocess.com/blog/the-lithium-mining-process-from-extraction-to-product-manufacturing/

Intelligence, G. T. (2023, October 30). The cost of green energy: Lithium mining's impact on nature and people. Mining Technology. https://www.mining-technology.com/analyst-comment/lithium-mining-negative-environmental-impact/

Jackson, R. (n.d.). The Effects of Climate Change. Climate Change: Vital Signs of the Planet. Retrieved February 15, 2023, from https://climate.nasa.gov/effects

Janubová, B. (2023). Green Extractivism in Lithium Triangle. Slovak Journal of International Relations, 21, 109–134. https://doi.org/10.53465/SJIR.1339-2751.2023.2.109-134

Jiajika Mine, Kangding pegmatite field, Kangding County, Garzê Autonomous Prefecture (Ganzi Autonomous Prefecture), Sichuan, China. (n.d.). Retrieved June 15, 2024, from https://www.mindat.org/loc-146947.html

Katwala, A. (n.d.). The spiralling environmental cost of our lithium battery addiction. Wired. Retrieved May 13, 2024, from https://www.wired.com/story/lithium-batteries-environment-impact/

Kelly, J. C., Wang, M., Dai, Q., & Winjobi, O. (2021). Energy, greenhouse gas, and water life cycle analysis of lithium carbonate and lithium hydroxide monohydrate from brine and ore resources and their use in lithium ion battery cathodes and lithium ion batteries. Resources, Conservation and Recycling, 174, 105762. https://doi.org/10.1016/j.resconrec.2021.105762

Koščová, M., Hellmer, M., Anyona, S., & Gvozdkova, T. (2018). Geo-Environmental Problems of Open Pit Mining: Classification and Solutions. E3S Web of Conferences, 41, 01034. https://doi.org/10.1051/e3sconf/20184101034

Kreif, N., Grieve, R., Hangartner, D., Turner, A. J., Nikolova, S., & Sutton, M. (2016). Examination of the Synthetic Control Method for Evaluating Health Policies with Multiple Treated Units. Health Economics, 25(12), 1514–1528. https://doi.org/10.1002/hec.3258

Kronbauer, A. (2022, May 2). Reducing the high water footprint of Lithium Production. VULCAN ENERGY RESOURCES. https://v-er.eu/blog/2022/05/02/reducing-the-high-water-footprint-of-lithium-production/

Lamberti, A. (2018) Mineral Resources delays production start at Wodgina lithium project. Retrieved May 11, 2024, from https://www.spglobal.com/marketintelligence/en/news-insights/trending/8aNvWcFS0hh2xgNq_Hbqlg2

Lappalainen, H., Rinne, M., Elomaa, H., Aromaa, J., & Lundström, M. (2024). Environmental impacts of lithium hydroxide monohydrate production from spodumene concentrate – A simulation-based life cycle assessment. Minerals Engineering, 209, 108632. https://doi.org/10.1016/j.mineng.2024.108632

Latief, Y. (2022, November 5). First Fit for 55 deal to bolster EV uptake. Smart Energy International. https://www.smart-energy.com/industry-sectors/electric-vehicles/first-fit-for-55-deal-to-bolster-ev-uptake/

Latitude.to. (n.d.). GPS coordinates of Wodgina mine, Australia. Latitude: -21.1811 Longitude: 118.6752. Latitude.to, Maps, Geolocated Articles, Latitude Longitude Coordinate Conversion. Retrieved June 15, 2024, from http://latitude.to:8080/articles-by-country/au/australia/127881/wodgina-mine

Li, K. T. (2020). Statistical Inference for Average Treatment Effects Estimated by Synthetic Control Methods. Journal of the American Statistical Association, 115(532), 2068–2083. https://doi.org/10.1080/01621459.2019.1686986

Lithium. (n.d.). Mineral Resources. Retrieved May 12, 2024, from https://www.mineralresources.com.au/our-business/lithium/

Lithium Liabilities: The untold threat to water in the rush to mine American lithium. (n.d.). Retrieved March 29, 2024, from https://cronkitenews.azpbs.org/howardcenter/lithium/stories/lithium-liabilities.html

Liu, X., & Li, S. (2021). A comparison analysis of the decoupling carbon emissions from economic growth in three industries of Heilongjiang province in China. Environmental Science and Pollution Research, 28, 1–16. https://doi.org/10.1007/s11356-021-15241-2

Lorca, M., Olivera Andrade, M., Escosteguy, M., Köppel, J., Scoville-Simonds, M., & Hufty, M. (2022). Mining indigenous territories: Consensus, tensions and ambivalences in the Salar de Atacama. The Extractive Industries and Society, 9, 101047. https://doi.org/10.1016/j.exis.2022.101047

Ma, J., Zhou, X., Xu, X., Xu, X., Gromov, S., & Lelieveld, J. (2022). Chapter 15—Ozone and aerosols over the Tibetan Plateau. In R. P. Singh (Ed.), Asian Atmospheric Pollution (pp. 287–302). Elsevier. https://doi.org/10.1016/B978-0-12-816693-2.00008-1

Marchegiani, P., Hellgren, J. H., & Gómez, L. (n.d.). Lithium extraction in Argentina: A case study on the social and environmental impacts.

Marx, P., Tamer, E., & Tang, X. (2024). Parallel Trends and Dynamic Choices. Journal of Political Economy Microeconomics, 2(1), 129–171. https://doi.org/10.1086/727363

Mas-Fons, A., Horta Arduin, R., Loubet, P., Pereira, T., Parvez, A. M., & Sonnemann, G. (2024). Carbon and water footprint of battery-grade lithium from brine and spodumene: A simulation-based LCA. Journal of Cleaner Production, 452, 142108. https://doi.org/10.1016/j.jclepro.2024.142108

McKay, D. (2023, May 22). The Paris Agreement and Global EV Adoption. Blossom EV Boutique Charging Solutions. https://blossomev.com/2023/05/22/the-paris-agreement-and-global-ev-adoption/

Moore, P. (2022, January 6). Argentina wants to triple its mining exports, amid social conflicts. Dialogue Earth. https://dialogue.earth/en/business/50042-argentina-triple-mining-exports-social-conflicts/

namadmin. (2019, October 3). Lithium Supply – Hard Rock vs. Brine. New Age Metals Inc. https://newagemetals.com/lithium-supply-hard-rock-vs-brine/

Niembro, A., & Sarmiento, J. (2021). Regional development gaps in Argentina: A multidimensional approach to identify the location of policy priorities. Regional Science Policy & Practice, 13(4), 1297–1328. https://doi.org/10.1111/rsp3.12322

OLAROZ LITHIUM FACILITY. (2021, November 29). Orocobre Limited. https://www.orocobre.com/operations/salar-de-olaroz/

Overview. (n.d.). Talison Lithium. Retrieved March 28, 2024, from https://www.talisonlithium.com/greenbushes-project

Overview—Eurostat. (n.d.). Retrieved June 25, 2024, from https://ec.europa.eu/eurostat/web/nuts

Palandrani, T. Y., Pedro. (2023, August 17). Theme Lab: Tracking Lithium's Journey in Chile's Salar de Atacama. Global X ETFs. https://www.globalxetfs.com/theme-lab-tracking-lithiums-journey-in-chiles-salar-de-atacama/

Petavratzi, E., & Gunn, G. (2022). Decarbonising the automotive sector: A primary raw material perspective on targets and timescales. Mineral Economics, 36. https://doi.org/10.1007/s13563-022-00334-2

Peters, J. F., Baumann, M., Zimmermann, B., Braun, J., & Weil, M. (2017). The environmental impact of Li-Ion batteries and the role of key parameters – A review. Renewable and Sustainable Energy Reviews, 67, 491–506. https://doi.org/10.1016/j.rser.2016.08.039

PorterGeo Database—Ore Deposit Description. (n.d.). Retrieved June 15, 2024, from https://portergeo.com.au/database/mineinfo.asp?mineid=mn1543

Press, A. (2024, March 14). "We will lose everything": Why South America's "lithium triangle" could devastate local communities. Fast Company. https://www.fastcompany.com/91058321/we-will-lose-everything-why-south-americas-lithium-triangle-could-devastate-local-communities

Rani, A. (2023, December 1). Develop obtains lithium mine underground development contract in WA. Mining Technology. https://www.mining-technology.com/news/develop-lithium-underground-wa/

Reporter, C. M. (n.d.). Beament's Develop wins Mt Marion contract. Mining Weekly. Retrieved May 12, 2024, from https://www.miningweekly.com/article/beaments-develop-wins-mt-marion-contract-2023-12-01

Rock, M. (2023, December 26). Environmental Impact of Open Pit Mining on Rivers. Coalition to SAVE the Menominee River, Inc. https://jointherivercoalition.org/open-pit-mining-description-unveiling-the-environmental-dangers/

Royal Berglee, P. (2016). 12.2 Australia. https://open.lib.umn.edu/worldgeography/chapter/12-2-australia/

Salar de Olaroz mine, Salar de Olaroz, Susques, Susques Department, Jujuy Province, Argentina. (n.d.). Retrieved June 15, 2024, from https://www.mindat.org/loc-310991.html

Salar del Hombre Muerto, Argentina. (n.d.). Retrieved June 15, 2024, from https://www.mindat.org/loc-229832.html

SeventhQueen, & Chomsky, R. (2023, October 6). Sustainable Lithium Extraction: How is Lithium Mined and Processed. Sustainable Review. https://sustainablereview.com/sustainable-lithium-extraction-how-is-lithium-mined-and-processed/

Shi, X., & Zhang, W. (2023). Characteristics of an underground stope channel supplied by atmospheric precipitation and its water disaster prevention in the karst mining areas of Guizhou. Scientific Reports, 13(1), 15892. https://doi.org/10.1038/s41598-023-43209-4

Simon, F., & Messad, P. (2023, May 28). Facing water stress: Chile's lithium industry under scrutiny in Atacama Desert. Www.Euractiv.Com. https://www.euractiv.com/section/energy-environment/news/facing-water-stress-chiles-lithium-industry-under-scrutiny-in-atacama-desert/

SQM. (2021). Sustainable-Lithium-English-2020430-2.pdf. Retrieved March 31, 2024, from https://sqmiodine.com/wp-content/uploads/2021/08/SQM-Sustainable-Lithium-English-2020430-2.pdf

SQM Lithium. (2023). Lithium History | About us | SQM Lithium. SQM. Retrieved May 2, 2024, from https://www.sqmlithium.com/en/nosotros/historia-del-litio/

Survey on Lithium sector in Chile_compressed.pdf. (n.d.). Retrieved March 26, 2024, from https://www.indianembassysantiago.gov.in/pdf/Survey%20on%20Lithium%20sector%20in%20Chile_compressed.pdf

Talison Lithium. (2018). Appendix G - Talison Greenbushes Expansion Dust Impact Assessment.pdf. Retrieved May 7, 2024, from https://www.epa.wa.gov.au/sites/default/files/Referral_Documentation/Appendix%20G%20-%20Talison%20Greenbushes%20Expansion%20Dust%20Impact%20Assessment.pdf

Talison Lithium. (n.d.). Retrieved May 2, 2024, from https://www.talisonlithium.com/

Thomson, O. (2023, July 5). Lithium success for Mt Marion. Australian Mining. https://www.australianmining.com.au/mt-marion-continues-to-see-lithium-success/

US EPA, O. (2014, September 12). What is Particle Pollution? [Collections and Lists]. https://www.epa.gov/pmcourse/what-particle-pollution

US EPA, O. (2016, April 19). Particulate Matter (PM) Basics [Overviews and Factsheets]. https://www.epa.gov/pm-pollution/particulate-matter-pm-basics

USGS. (2018). 2018 Mineral Yearbook. Myb1-2018-lithium.pdf. Retrieved June 27, 2024, from https://pubs.usgs.gov/myb/vol1/2018/myb1-2018-lithium.pdf

Vera, M. L., Torres, W. R., Galli, C. I., Chagnes, A., & Flexer, V. (2023). Environmental impact of direct lithium extraction from brines. Nature Reviews Earth & Environment, 4(3), 149–165. https://doi.org/10.1038/s43017-022-00387-5

Wang, J., & Ogawa, S. (2015). Effects of Meteorological Conditions on PM2.5 Concentrations in Nagasaki, Japan. International Journal of Environmental Research and Public Health, 12, 9089–9101. https://doi.org/10.3390/ijerph120809089

Wang, R., Cui, K., Sheu, H.-L., Wang, L.-C., & Liu, X. (2023). Effects of Precipitation on the Air Quality Index, PM2.5 Levels and on the Dry Deposition of PCDD/Fs in the Ambient Air. Aerosol and Air Quality Research, 23(4), 220417. https://doi.org/10.4209/aaqr.220417

Yang, Q., Yuan, Q., Li, T., Shen, H., & Zhang, L. (2017). The Relationships between PM2.5 and Meteorological Factors in China: Seasonal and Regional Variations. International Journal of Environmental Research and Public Health, 14(12), 1510. https://doi.org/10.3390/ijerph14121510

Young, E. (2019). Dardanup lithium waste dump plan shows how shamefully backward we are. Retrieved June 28, 2024, from https://www.smh.com.au/national/enormous-lithium-waste-dump-plan-shows-how-shamefully-backward-we-are-20190621-p52054.htm

Zhang, B., Qi, F., Gao, X., Li, X., Shang, Y., Kong, Z., Jia, L., Meng, J., Guo, H., Fang, F., Liu, Y., Jiang, X., Chai, H., Liu, Z., Ye, X., & Wang, G. (2022). Geological characteristics, metallogenic regularity, and research progress of lithium deposits in China. China Geology, 5(4), 734–767. https://doi.org/10.31035/cg2022054

Zheng, M. (2023, March 31). The Environmental Impacts of Lithium and Cobalt Mining. Earth.Org. https://earth.org/lithium-and-cobalt-mining/

Appendix A

TABLE 1:OVERVIEW OF THE PRIMARY LITHIUM BRINE MINES IN THE SOUTH AMERICAN LITHIUM TRIANGLE.

COUNTRIES (Lithium Triangle)	BOLIVIA	CHILE	ARGENTINA
Salar Name	Uyuni	Atacama	Hombre Muerto
Altitude (km)	3.7	2.3	4.3
Area (km2)	8,000	3,000	570
Li Concentration (%/wt)	0.0350	0.1500	0.0620
Mg/Li Ratio	18.6	6.4	1.4
Evaporation (mm / Year)	1,500	3,200	2,300

Source: Survey on Lithium sector in Chile_compressed.pdf. (n.d.). Retrieved March 26, 2024, from https://www.indianembassysantiago.gov.in/pdf/Survey%20on%20Lithium%20sector%20in%20Chile_compressed.pdf

Appendix B

1.14 CO2 Emissions- Treated vs Synthetic Units on Key Predictor Values

Table1a. CO2 Emissions from Lithium Mining in NOA Predictor Means before The Paris Agreement

Variables	Treated	Synthetic	Sample Mean
HDI	0.811	0.811	0.816
CO2_lag	4,682.940	3,907.527	7,397.260
CO2_2008	4,228.820	4,033.900	7,987.858
CO2_2020	3,656.200	3,702.278	7,457.844

Table1b. CO2 Emissions from Lithium Mining in Western Australia Predictor Means before The Paris Agreement

Variables	Treated	Synthetic	Sample Mean
HDI	0.930	0.895	0.912
CO2_lag	1,802.884	2,297.076	15,727.750
C02_2008	1,816.870	1,820.335	16,311.470
CO2_2020	2,180.750	2,127.831	17,224.200

Table1c. CO2 Emissions from Lithium Mining in Antofagasta Predictor Means before The Paris Agreement

Variables	Treated	Synthetic	Sample Mean

HDI	0.829	0.825	0.787
CO2_lag	4,395.053	4,331.980	15,875.670
CO2_2008	4,098.870	4,362.906	17,610.010
CO2_2020	8,356.830	6,567.640	17,732.420

Table1d. CO2 Emissions from Lithium Mining in Sichuan Predictor Means before The Paris Agreement

Variables	Treated	Synthetic	Sample Mean
HDI	0.621	0.621	0.655
CO2_lag	53,461.640	47,438.340	243,523.400
CO2_2008	46,527.470	44,981.770	244,383.400
CO2_2020	55,246.490	63,698.940	360,115.200

1.15 CO2 Emissions- Weights of Synthetic Units

Table2a. Region Weights in Synthetic NOA

Weights	Regions	Region_id
0.006	ARGr101	1
0.441	ARGr103	3
0.023	ARGr104	4
0.016	ARGr105	5
0.515	ARGr106	6

Table2b. Region Weights in Synthetic Western Australia[10]

Weights	Regions	Region_id
0	AUSr101	1
0	AUSr102	2
0	AUSr103	3
0.001	AUSr104	4
0.152	AUSr106	6
0.847	AUSr107	7
0	AUSr108	8

Table2c. Region Weights in Synthetic Antofagasta

Weights	Regions	Region_id
0.569	CHLr101	1
0	CHLr103	3
0	CHLr104	4

[10] Due to predictor limitations, regional analysis under CO2 emissions for Western Australia, range from regions 1-8

0.045	CHLr105	5
0	CHLr106	6
0	CHLr107	7
0	CHLr108	8
0	CHLr109	9
0	CHLr110	10
0	CHLr111	11
0.386	CHLr112	12
0	CHLr113	13

Table2d. Region Weights in Synthetic Sichuan[11]

Weights	Regions	Region_id
0.002	CHNr101	1
0.002	CHNr102	2
0.007	CHNr103	3
0.007	CHNr104	4
0.002	CHNr105	5
0.005	CHNr106	6
0.005	CHNr107	7
0.366	CHNr108	8
0.001	CHNr109	9
0.004	CHNr110	10
0.006	CHNr111	11
0.007	CHNr112	12
0.007	CHNr113	13

[11] Due to predictor limitations, regional analysis under CO2 emissions for Sichuan, range from regions 1-31

0.009	CHNr114 14
0.005	CHNr115 15
0.007	CHNr116 16
0.006	CHNr117 17
0.011	CHNr118 18
0.004	CHNr119 19
0.009	CHNr120 20
0.008	CHNr121 21
0.007	CHNr122 22
0.010	CHNr124 24
0.019	CHNr125 25
0.047	CHNr126 26
0.006	CHNr127 27
0.014	CHNr128 28
0.391	CHNr129 29
0.004	CHNr130 30
0.022	CHNr131 31

1.16 PM2.5 Emissions- Treated vs Synthetic Units on Key Predictor Values

Table3a. PM2.5 Emissions from Lithium Mining in NOA Predictor Means before The Paris Agreement

Variables	Treated	Synthetic	Sample Mean
Humidity	49.527	51.615	59.833
Precipitation	0.028	0.020	0.027
PM2.5_lag	6.639	5.391	10.401
PM2.5_2008	6.030	5.642	11.356
PM2.5_2020	5.660	6.472	13.722

Table3b. PM2.5 Emissions from Lithium Mining in Western Australia Predictor Means before The Paris Agreement

Variables	Treated	Synthetic	Sample Mean
Humidity	40.642	41.739	58.858
Precipitation	0.012	0.012	0.022
PM2.5_lag	1.136	1.227	8.425
PM2.5_2008	0.980	0.957	7.347
PM2.5_2020	0.800	0.871	6.624

Table3c. PM2.5 Emissions from Lithium Mining in Antofagasta Predictor Means before The Paris Agreement

Variables	Treated	Synthetic	Sample Mean

Humidity	30.158	40.897	65.828
Precipitation	0.004	0.005	0.045
PM2.5_lag	4.229	4.029	30.155
PM2.5_2008	4.460	4.298	32.312
PM2.5_2020	3.810	3.461	25.887

Table3d. PM2.5 Emissions from Lithium Mining in Sichuan Predictor Means before The Paris Agreement

Variables	Treated	Synthetic	Sample Mean
Humidity	71.649	71.647	63.974
Precipitation	0.043	0.043	0.035
PM2.5_lag	105.774	97.576	457.366
PM2.5_2008	99.380	98.259	484.726
PM2.5_2020	78.440	80.062	375.665

1.17 CO2 Emissions- Weights of Synthetic Units

Table4a. Region Weights in Synthetic NOA

w.weights	unit.names	unit.numbers
0.106	ARGr101	1
0	ARGr103	3
0.894	ARGr104	4
0	ARGr105	5

0	ARGr106	6

Table4b. Region Weights in Synthetic Western Australia

w.weights	unit.names	unit.numbers
0.002	AUSr101	1
0.001	AUSr102	2
0.002	AUSr103	3
0.662	AUSr104	4
0.001	AUSr106	6
0.329	AUSr107	7
0	AUSr108	8
0.003	AUSr109	9

Table4c. Region Weights in Synthetic Anfogasta

w.weights	unit.names	unit.numbers
0.095	CHLr101	1
0.897	CHLr103	3
0	CHLr104	4
0	CHLr105	5
0	CHLr106	6
0	CHLr107	7
0	CHLr108	8
0	CHLr109	9
0	CHLr110	10
0	CHLr111	11

0	CHLr112	12
0.008	CHLr113	13

Table4d. Region Weights in Synthetic Sichuan

w.weights	unit.names	unit.numbers
0.001	CHNr101	1
0.001	CHNr102	2
0.001	CHNr103	3
0.001	CHNr104	4
0.002	CHNr105	5
0.001	CHNr106	6
0.002	CHNr107	7
0.180	CHNr108	8
0	CHNr109	9
0	CHNr110	10
0.001	CHNr111	11
0.001	CHNr112	12
0	CHNr113	13
0	CHNr114	14
0.001	CHNr115	15
0.001	CHNr116	16
0.001	CHNr117	17
0.001	CHNr118	18
0	CHNr119	19
0	CHNr120	20
0.057	CHNr121	21

0	CHNr122	22
0.585	CHNr124	24
0.064	CHNr125	25
0.090	CHNr126	26
0.002	CHNr127	27
0.002	CHNr128	28
0.002	CHNr129	29
0.001	CHNr130	30
0.002	CHNr131	31
0	CHNr132	32

1.18 CO2 Emissions- Gap plots, Treated- Synthetic Unit

Fig1a. Gap in Per Capita CO2 Emissions between NOA and Synthetic NOA

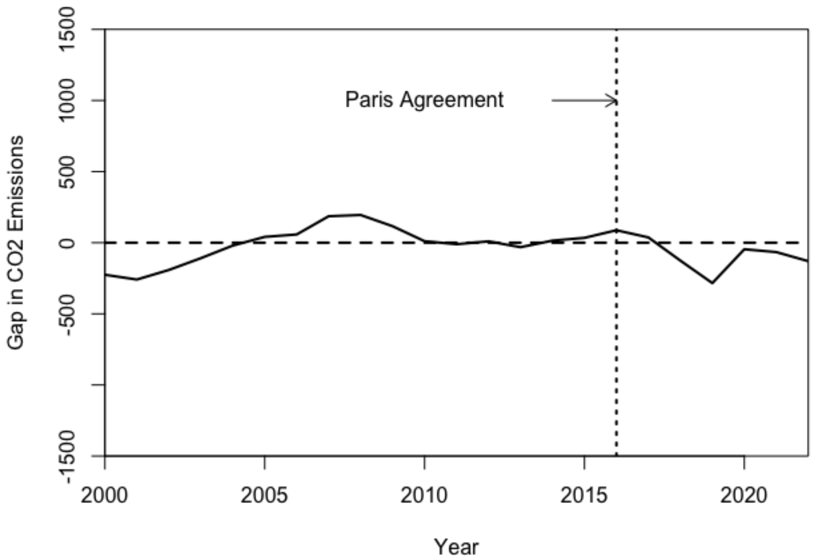


Fig1b. Gap in Per Capita CO2 Emissions between Western Australia and Synthetic Western Australia

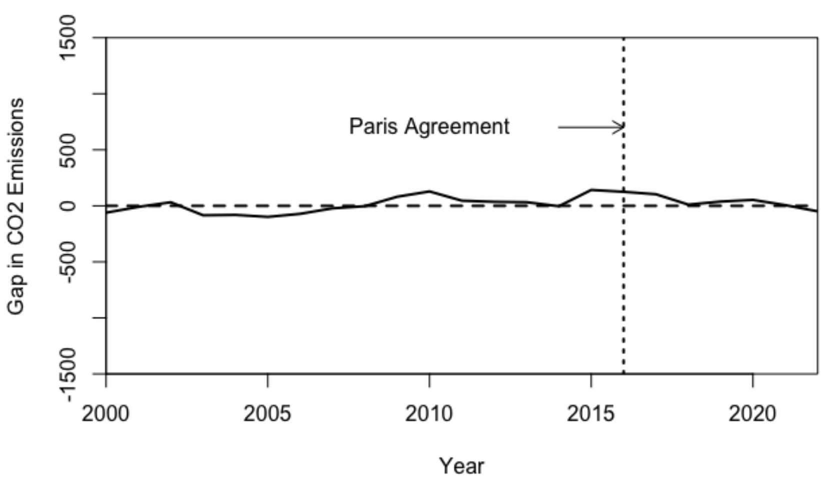


Fig1c. Gap in Per Capita CO2 Emissions between Antofagasta and Synthetic Antofagasta

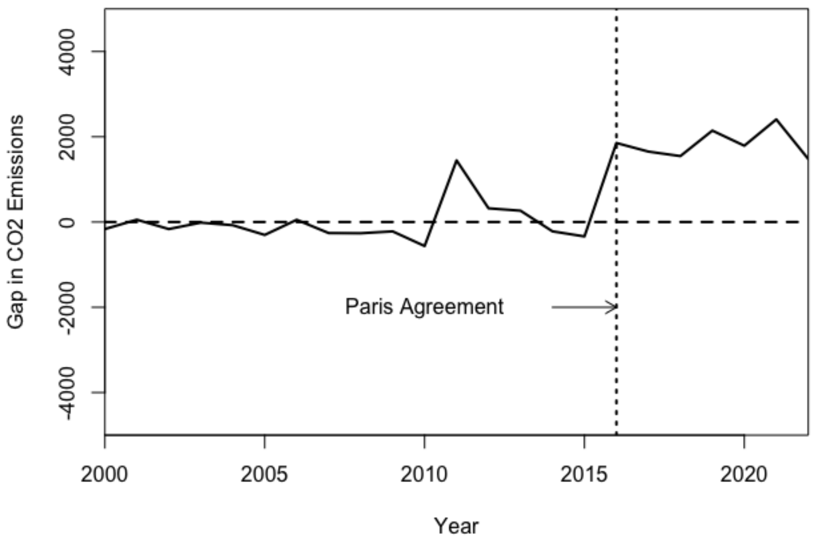
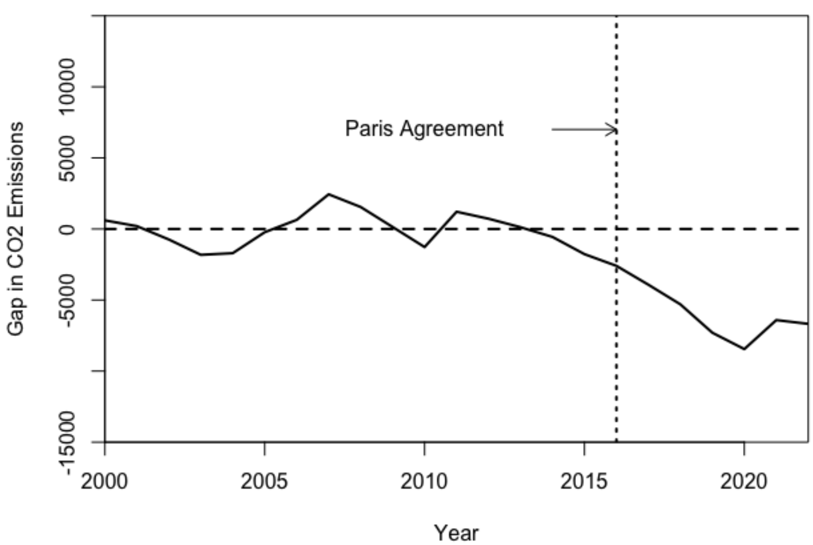


Fig1d. Gap in Per Capita CO2 Emissions between Sichuan and Synthetic Sichuan



1.19 PM2.5 Emissions- Gap plots, Treated- Synthetic unit

Fig2a. Gap in Per Capita PM2.5 Emissions between NOA and Synthetic NOA

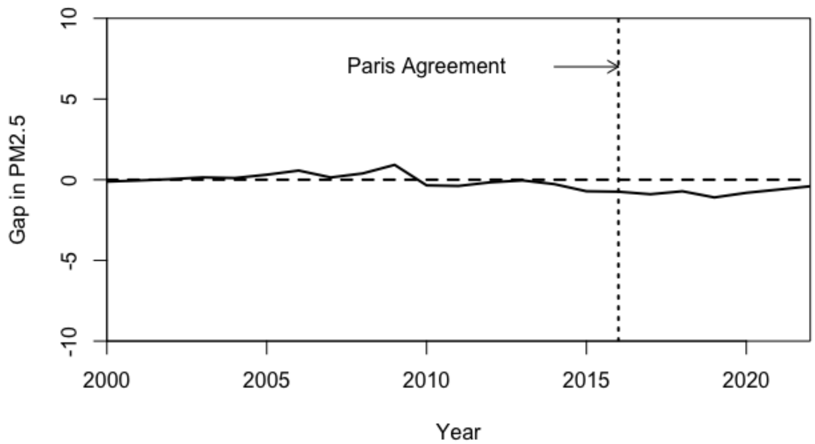


Fig2b. Gap in Per Capita PM2.5 Emissions between Western Australia and Synthetic Western Australia

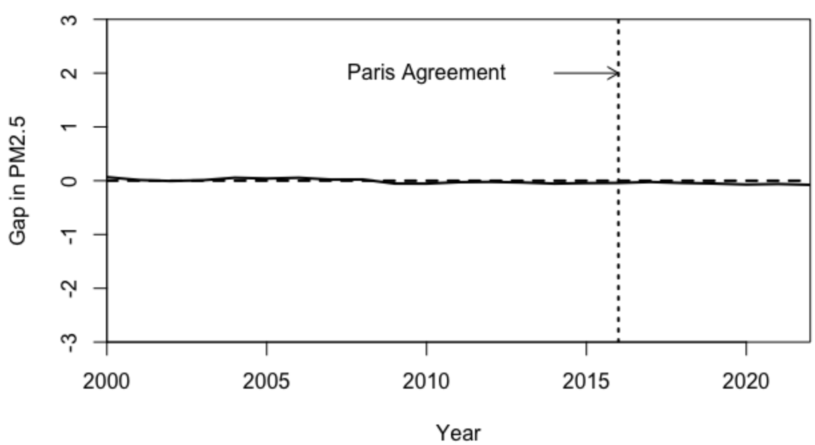


Fig2c. Gap in Per Capita PM2.5 Emissions between Antofagasta and Synthetic Antofagasta

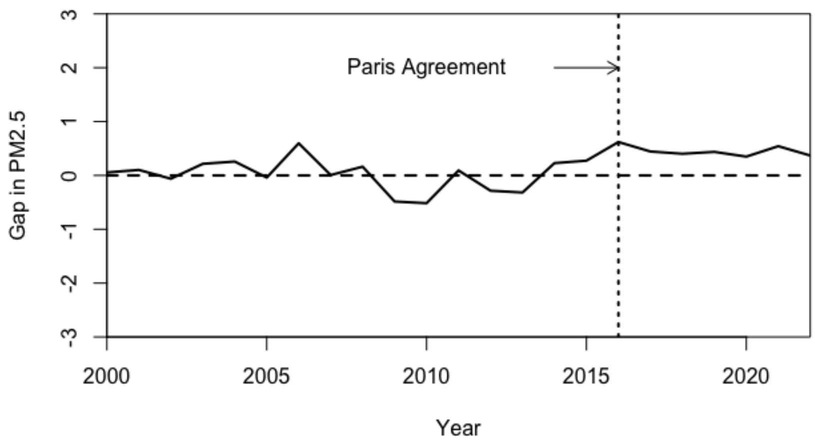
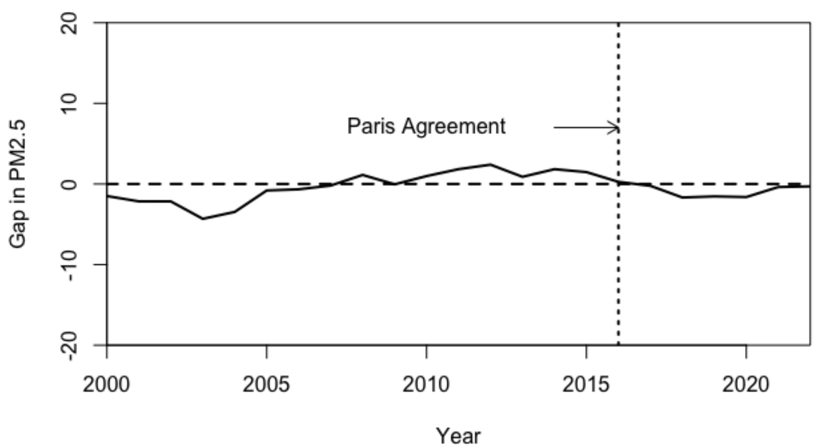


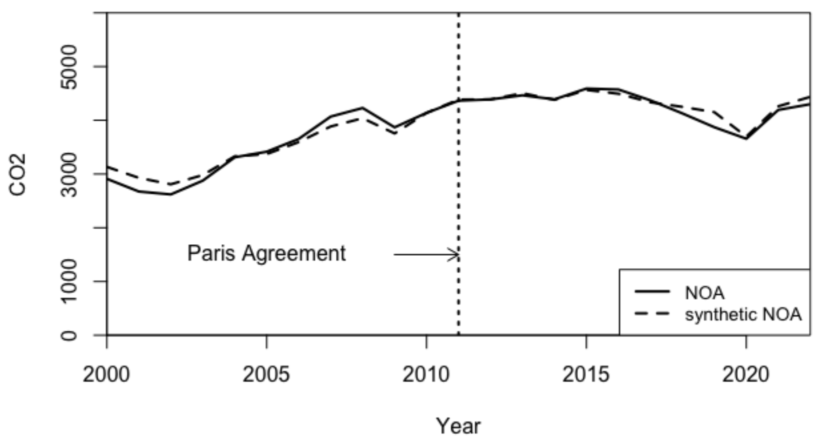
Fig2d. Gap in Per Capita PM2.5 Emissions between Sichuan and Synthetic Sichuan



APPENDIX C

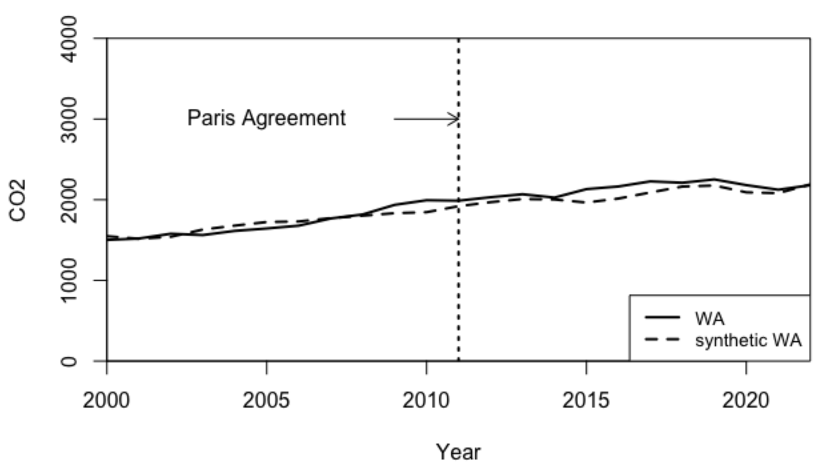
1.20 CO2 Emissions- In-Time Placebo Test

Fig3a. Placebo In-Time Tests



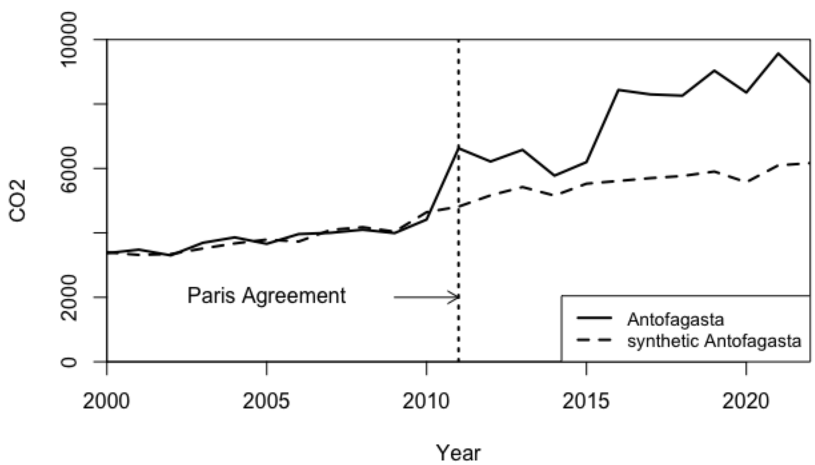
The placebo intervention was introduced in 2011, five years prior to the actual policy changes.

Fig3b. Placebo In-Time Tests



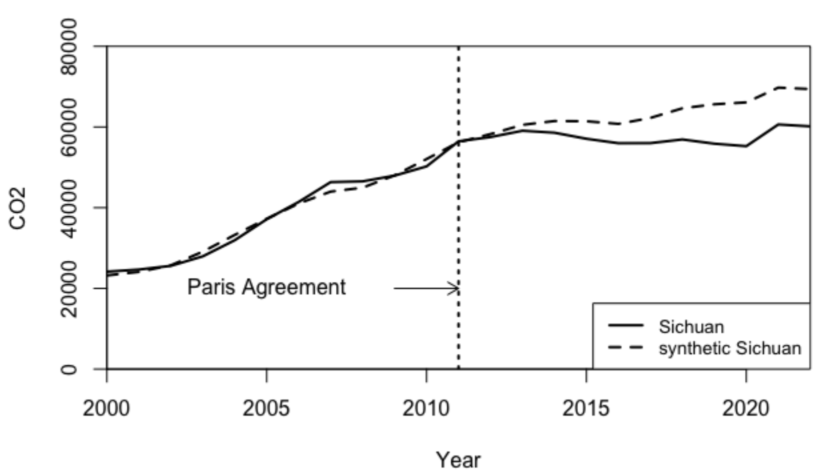
The placebo intervention was introduced in 2011, five years prior to the actual policy changes.

Fig3c. Placebo In-Time Tests



The placebo intervention was introduced in 2011, five years prior to the actual policy changes.

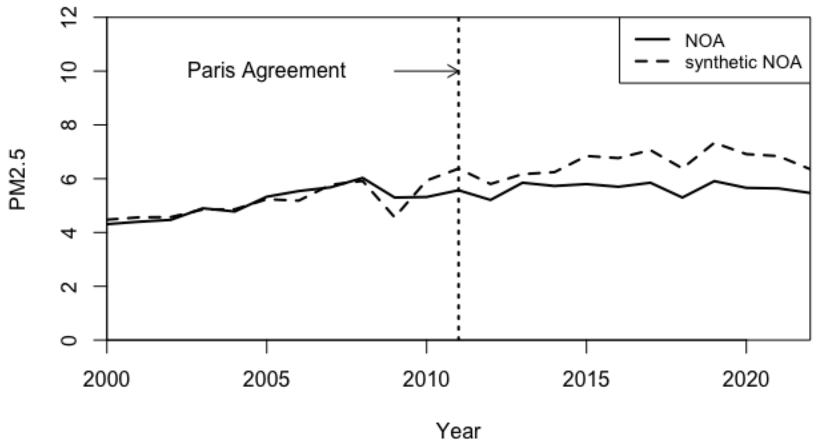
Fig3d. Placebo In-Time Tests



The placebo intervention was introduced in 2011, five years prior to the actual policy changes.

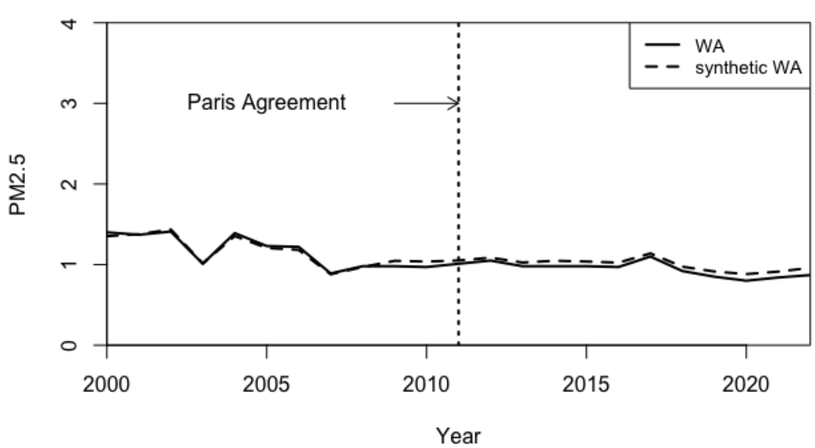
1.21 PM2.5 Emissions- In-Time Placebo Test

Fig4a. Placebo In-Time Tests



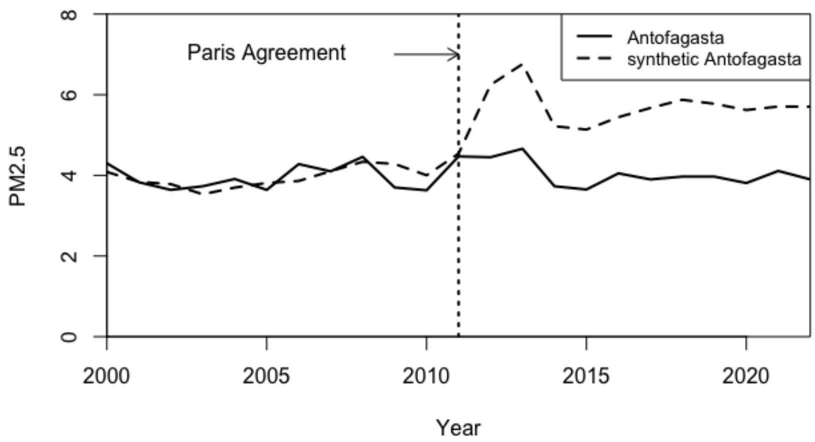
The placebo intervention was introduced in 2011, five years prior to the actual policy changes.

Fig4b. Placebo In-Time Tests



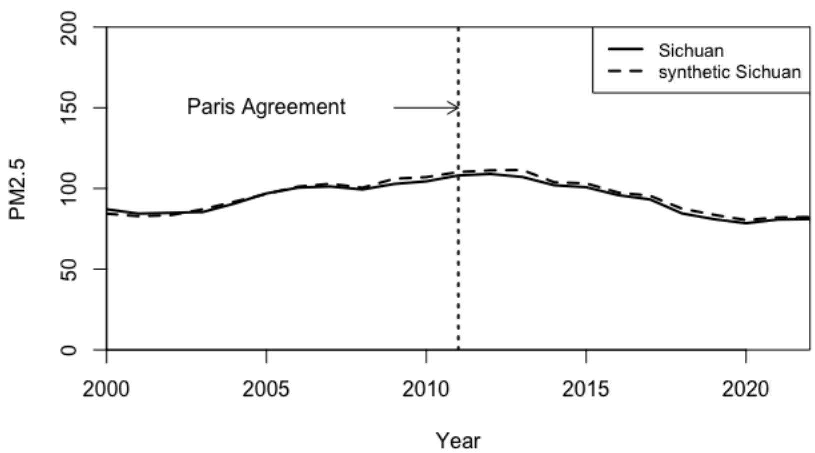
The placebo intervention was introduced in 2011, five years prior to the actual policy changes.

Fig4c. Placebo In-Time Tests



The placebo intervention was introduced in 2011, five years prior to the actual policy changes.

Fig4d. Placebo In-Time Tests



The placebo intervention was introduced in 2011, five years prior to the actual policy changes.

1.22 CO2 Emissions- In-Space Placebo Test

Fig5a. Per Capita CO2 Emissions Gap in NOA and Placebo Gaps for the Control Countries

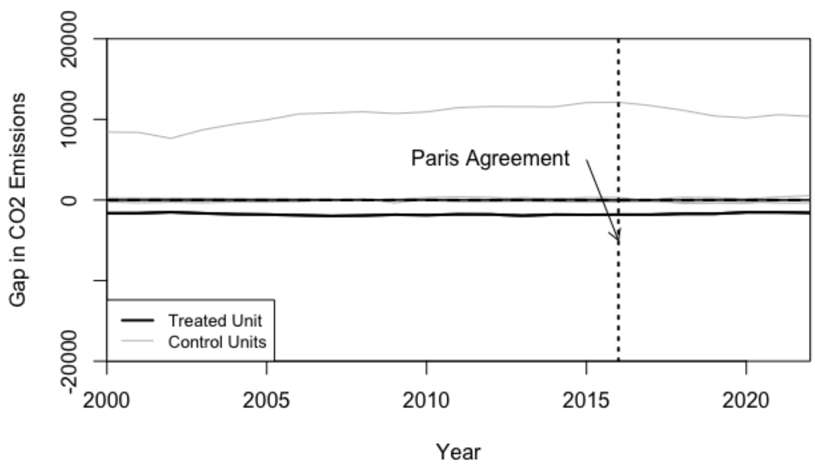


Fig5b. Per Capita CO2 Emissions Gap in Western Australia and Placebo Gaps for the Control Countries

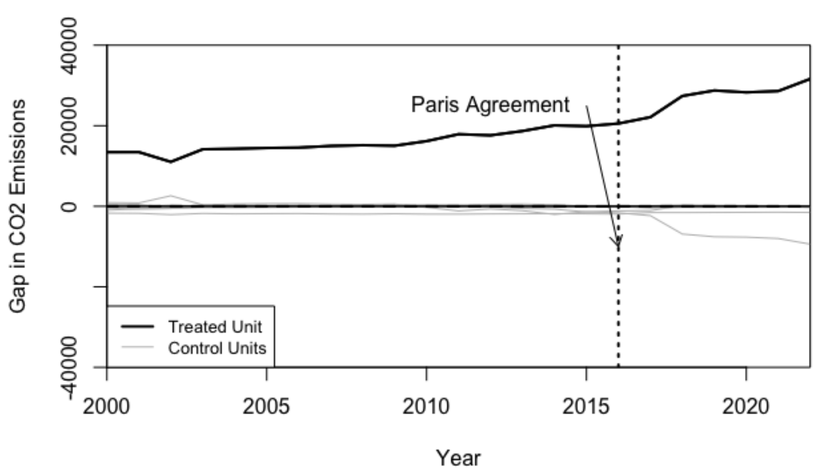


Fig5c. Per Capita CO2 Emissions Gap in Antofagasta and Placebo Gaps for the Control Countries

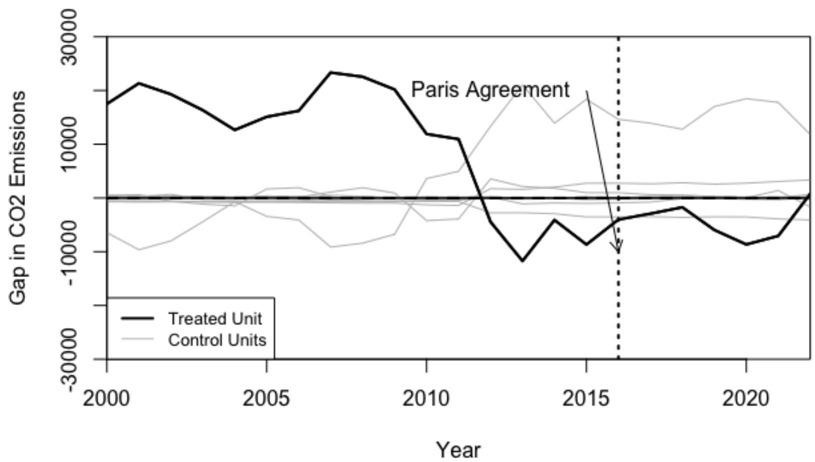
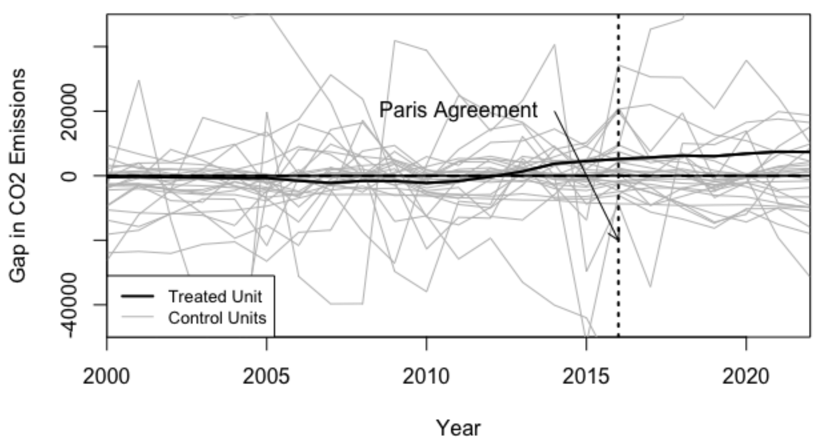


Fig5d. Per Capita CO2 Emissions Gap in Sichuan and Placebo Gaps for the Control Countries



1.23 PM2.5 Emissions- In-Space Placebo Test

Fig6a. Per Capita PM2.5 Emissions Gap in NOA and Placebo Gaps for the Control Countries

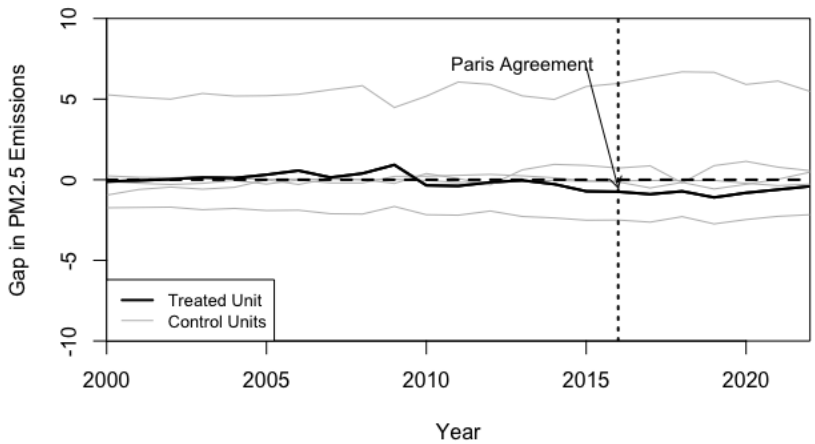


Fig6b. Per Capita PM2.5 Emissions Gap in Western Australia and Placebo Gaps for the Control Countries

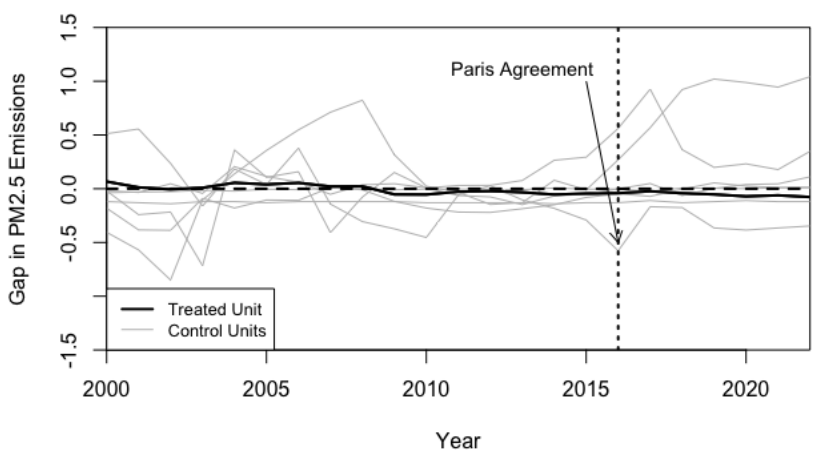


Fig6c. Per Capita PM2.5 Emissions Gap in Antofagasta and Placebo Gaps for the Control Countries

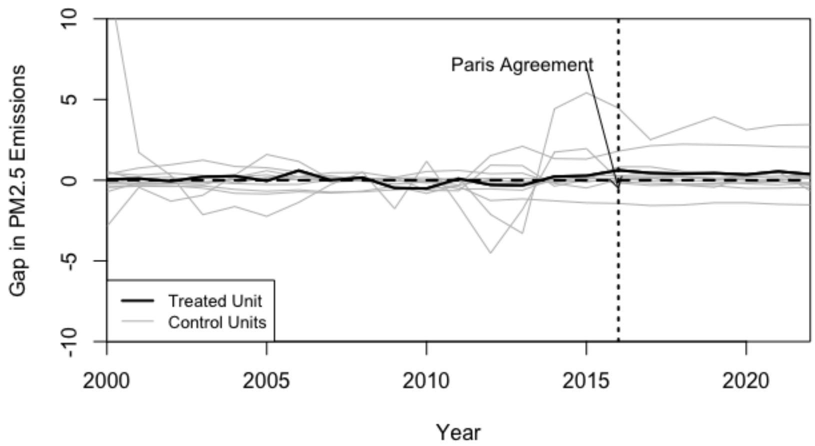
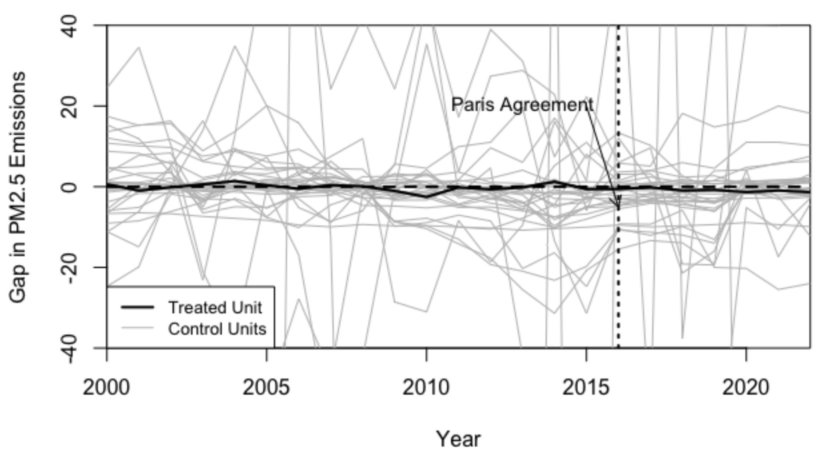


Fig6d. Per Capita PM2.5 Emissions Gap in Sichuan and Placebo Gaps for the Control Countries



1.24 Robustness Check- CO2 Emissions

Fig7a. Path plot of CO2 Emissions from mining during 2000:2018

Western Australia vs Synthetic Western Australia

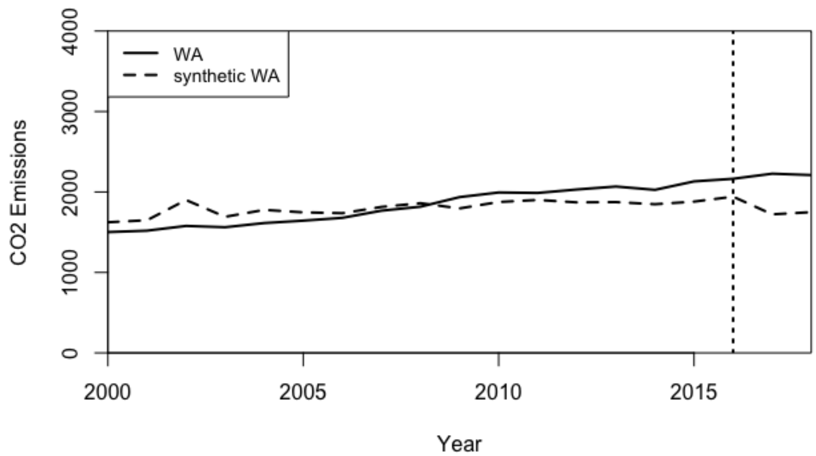
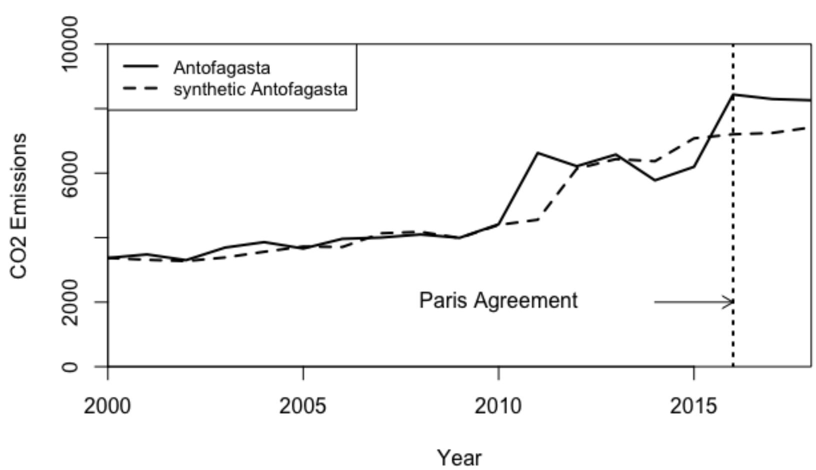


Fig7b. Path plot of CO2 Emissions from mining during 2000:2018

Antofagasta vs Synthetic Antofagasta



1.25 Robustness Check- PM2.5 Emissions

Fig8a. Path plot of PM2.5 Emissions from mining during 2000:2018

Western Australia vs Synthetic Western Australia

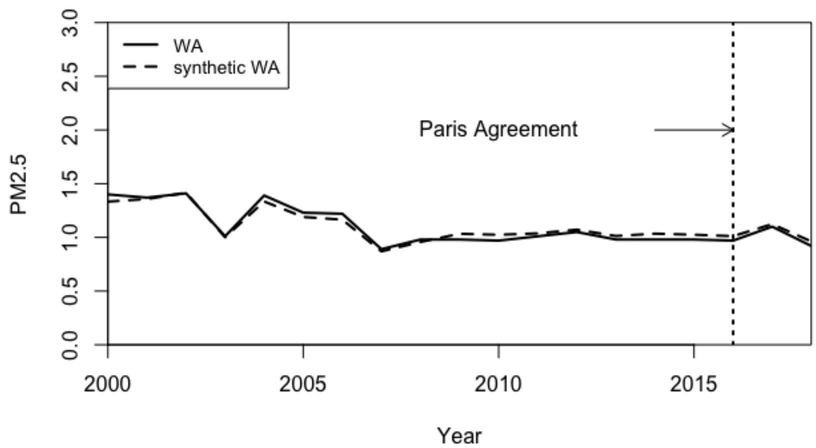


Fig8b. Path plot of PM2.5 Emissions from mining during 2000:2018

Antofagasta vs Synthetic Antofagasta

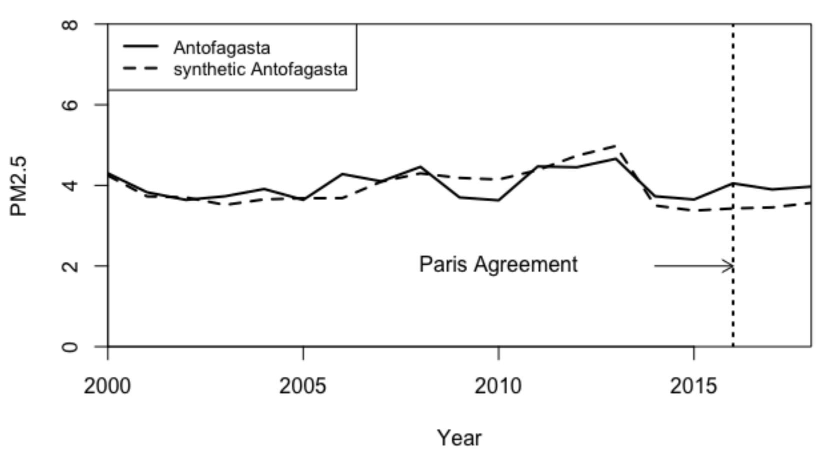


Fig8c. Path plot of PM2.5 Emissions from mining during 2000:2018

Sichuan vs Synthetic Sichuan