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ABSTRACT

Spillover Effects of Energy Transition Metals in Chile

This paper examines the impact of spillover effects of energy transition metals on the Chilean economy. With the increasing demand for metals like copper and lithium due to the growth in renewable energies and electromobility, metal abundant countries like Chile must ready themselves to remain active players in the international arena. The study aims at identifying the causal relationships among these energy transition metals and other major assets like gold and bitcoin, and how they have given shape to Chile's economy, especially during the uncertain times of the covid pandemic. Our Structural Vector Autoregressive models suggest that Chile has been more prone to US-led shocks than Chinese shocks, even though its economy depends heavily on China. In addition, bitcoin shocks seem to have also contributed to Chile's transition to a metals-based economy, likely as a result of bitcoin's extensive use of energy and the uncertainty and volatility that characterize post-covid times.

JEL Classification: F62, G15, L61

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1 Introduction

Copper and lithium are fast growing and widely utilized commodities with various applications in our daily lives. Countries like Chile have traditionally relied on strong exports, especially from the mining sector, with copper coming right on top. Various studies have projected the worldwide consumption of metals, including copper and lithium, will skyrocket in the near future. This will mainly be due to a boost in renewable energies and an upsurge in electromobility associated to decarbonization policies.[1] If there is going to be a concerted effort for a transition towards a net-zero emission global economy, it will certainly be commodity-intensive and will require significant quantities of critical metals.

With a growing demand for energy transition metals, mining reserve-abundant countries like Chile could become relevant players. In this paper we ask: what could be the impact of these global trends on the Chilean Economy? In particular, is there a connection between these energy transition metals and safe-haven assets like gold or risky assets like bitcoin? Also, what role does energy play? For instance, are both the US and the Chinese energy sectors equally important as shaping forces of Chile's economy? Has the covid pandemic brought about a major change in these trends? And last, is Chile already prepared to become a big player and use the momentum to take advantage of energy transition metals in the coming years? In short, our goal will be to study the spillover effects among these energy transition metals and assets, especially in the context of covid times and Chile.

In this paper we rely on Structural Vector Autoregressive (SVAR) models with a recursive scheme to identify the causal relationships among the variables of interest. We will be estimating two versions of the same model, the first one with a focus on the renewable energy international market and copper as the triggering mechanisms, and the second one with a focus on the electromobility sector and lithium. For our models, the S&P Global clean energy index and the S&P Kensho index, as proxies for global activity in the clean energy and electromobility sectors, respectively, will have an impact on Chinese activity (through the Shanghai composite index, SSEC), which remains a major player in both these sectors. These variables will give shape to several commodity prices (e.g. metals), including bitcoin (BTC), which will made their way into the Chilean economy (S&P IPSA index). Our database was retrieved from many sources like the Chilean Copper Commission (cochilco.cl), the Central Bank of Chile (bcentral.cl), tradingeconomics.com, investing.com, ourworldindata.org, bloomberg.com, spglobal.com, and the

[1] See, among many others, Berahab, (2022); Boer et al., (2021); Dong et al., (2019); Gonzalez et al., (2020); Hersh, (2019); Hund et al., (2020); Schipper et al., (2018); Watari et al. (2018, 2020, 2021); the International Energy Agency, (2022); International Monetary Fund, (2021); and the World Bank, (2021).

U.S. Geological Survey, among others.

Several works have studied the behavior, volatility, and also the safe-haven properties of crypto-assets like bitcoin and precious metals like gold. In general, they find evidence on their interconnectedness, especially in highly volatile periods such as the covid pandemic and the Ukraine war.[2] It will be interesting to test how these assets interact both prior and during the covid, which is what we will do for both our models in a section below. In particular, the study of the spillover effects of energy transition metals in Chile has not yet been fully addressed, but we intend to fill this gap in the literature with our empirical analysis below.

Moreover, we believe the timing is right, as Chile finds itself at the crossroads when it comes to the development of its renewable and electromobility energy sectors, and it is now poised to remain an important contender in the international markets. Indeed, if the future turns out to be renewable energy intensive, it will require significant quantities of copper and lithium to satisfy the deployment of clean energy and electromobility technologies. The price of these metals could thus skyrocket several times, and the challenge for Chile's policy makers should be aimed at facilitating the development of new projects—that is, to increase its competitiveness in the long term while embracing the economic benefits of energy transition.

Our results suggest that, during covid, Chile has surprisingly found itself more shaken by US-led than Chinese shocks, even when Chile's economy depends heavily on China. In particular, our impulse response function (IRF) analysis found that a one-standard deviation structural shock to the S&P Global clean energy index or the S&P Kensho index, had a cumulative effect of 2 percentage points on Chile's IPSA in roughly a week. Bitcoin, too, shows a significant cumulative effect of slightly less than 2 percentage points. Our follow-up variance decomposition analysis confirms these results, especially for the renewable energy model.

The paper is organized as follows. We discuss the global context as well as Chile's main energy transition metals, copper and lithium, in section 2. We also discuss the all-too-often overlooked connection between cryptos (and the underlying technology, the blockchain) with transition metals in section 3. Our thoughts about identification and our SVAR specification are offered in section 4, while a full-fledged empirical analysis is shown under section 5. At last, section 6 concludes.

[2]See, for example, Adekoya et al. (2022); Agnese and Thoss (2021); Bildirici and Sonustun (2022); Doumenis et al. (2021); Elsayed et al. (2021); Erdas (2018); Fasanya et al. (2021); Hassan et al. (2021); Mensi et al. (2018, 2019); Yatie (2022a, 2022b);.and Wen et al. (2022).

2 Chile's energy transition metals

2.1 Global context

Energy transition, as an idea, aims at an economy based on net-zero emissions, in which fossil-based systems of energy production and consumption will evolve to renewable energy sources like wind and solar, as well as lithium-ion batteries. In this context it should be noted that the renewable energy installed capacity, like solar and wind, has increased notably from 2016 to 2018 in 17 transition economies (Pablo-Romero et al., 2021). In addition to that, estimations for the copper sector suggest a three-fold increase from 2016 to 2050 (Dong et. al., 2019), and a x18 to x20 increase in lithium from 2020 to 2050 (Xu et al., 2020)—the latter being largely affected by the development of the electric vehicle industry. Arguably, these trends would take place under the global framework laid out by 'The Paris Agreement' (see Fekete, 2021; and Tang et al., 2021).

Regardless of how far-fetched this transition might appear, it will certainly require significant quantities of critical metals. A significant increase in the demand for metals like copper and lithium is therefore expected as widely attested by the recent literature.[3] The resulting higher prices might in turn create strong incentives that will foster supply and curb demand (Tilton et al., 2018).

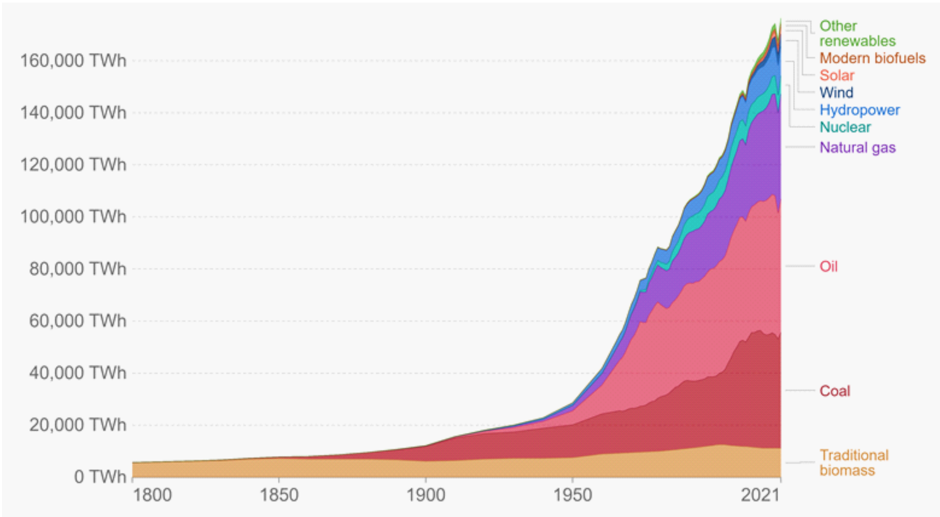
Comparatively though, fossil fuels like oil, carbon, and gas, still claim the lion's share of energy consumption worldwide, with a consumption in the neighborhood of 140,000 Twh in 2021, as shown in Figure 1. Even when growing rapidly (hydropower, most remarkably), renewables are still lagging behind by a big margin, with a consumption of around 8,000 Twh in 2021.

The International Energy Agency (2022) offers an interesting breakdown on the consumption of major metals. For instance, as suggested by Figure 2, it is very telling to see that the electric car industry employs more copper and lithium than conventional cars. Likewise, it is also worth mentioning the increasing amount of both these metals (notably copper) that go in the generation of cleaner energy technologies, as compared to the traditional ones based on fossil fuels, like coal and gas.

It is thus of utmost importance for mining countries like Chile, which might become a relevant player in the near future, to study the synergies and potential impact of these critical metals, especially copper and lithium, on the local economy. This we set out to do in the following sections, starting with an overview of the copper and lithium sectors in Chile.

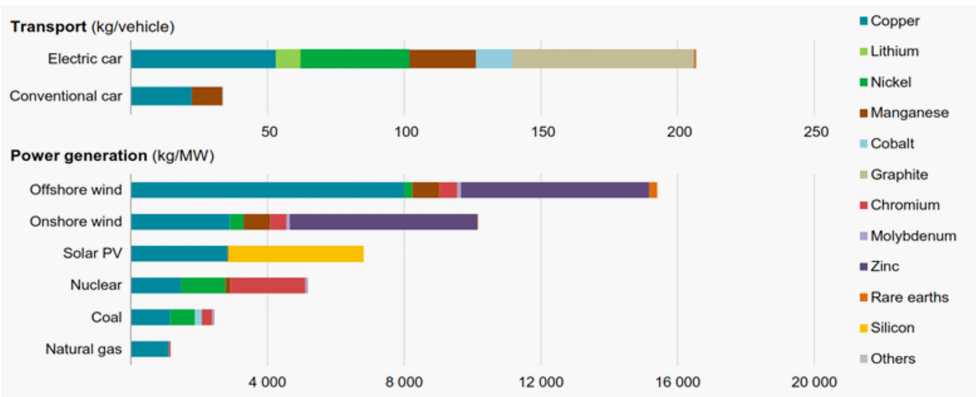
[3] See Boer et al. (2021); Dong et al. (2019); Hersh (2019); Hund et al. (2020); Schipper et al. (2018); Watari et al. (2018, 2020, 2021); the International Energy Agency (2022); International Monetary Fund (2021); and the World Bank (2021), among others.

Figure 1: Global primary energy consumption by source



Source: Our World in Data (2021).

Figure 2: Consumption of metals in selected sectors



Source: International Energy Agency (2022).

2.2 Copper

The red metal has many industrial applications nowadays—it is a soft, malleable, and ductile material with very high thermal and electrical conductivity. As shown in Table 1, construction and electrical grid remain its main uses.

The Chilean economy, in particular, has traditionally relied on strong exports from the mining sector, with copper representing a 51% of total exports in 2014 (Lefevre et al., 2017). Moreover, mining is the economic sector with the largest contribution to tax revenue (Cantallopts, 2016), and copper mining has claimed an average of 9.9% of Chile's GDP in 1996-2016, ranging from 3.6% in 1998 (during the Asian crisis) to a peak of 19.6% in 2006 (International Copper Association, 2017).

Table 1: Uses and industrial applications of copper, world

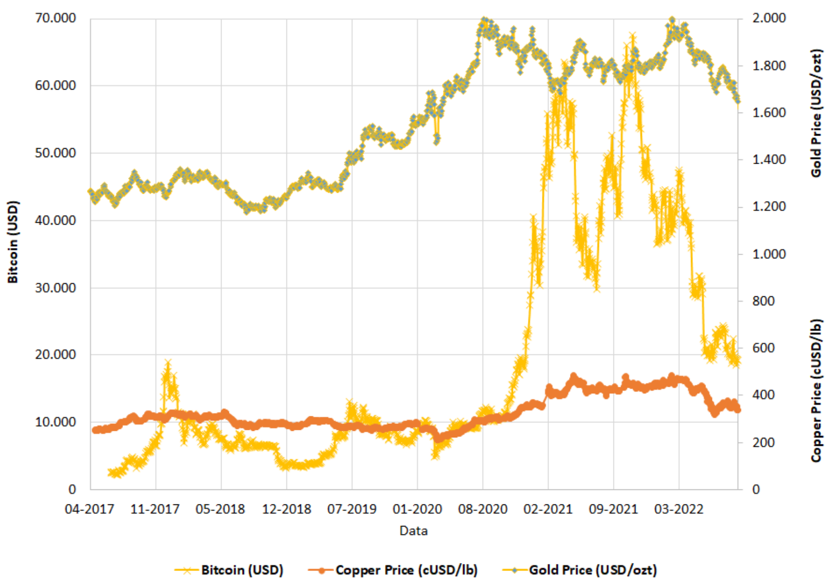
Construction	31%
Electrical grid	24%
General consumption	24%
Transport	11%
Industrial Machinery	10%
	100%

Source: Cochilco (2017).

Chile's GDP has been shaped by the mining sector and its value has constantly depended on the price of copper in international markets (Cantallopts, 2019). During recent years, copper along with gold and other major metals, have experienced a bull run probably due to world uncertainty, but also due to covid lockdowns and trade restrictions resulting from the Ukraine war.

Another less traditional asset, bitcoin, has also seen significant appreciation in the price, probably because of the same reasons, as well as on its very speculative and disruptive nature. These price fluctuations, in particular that of copper's, have affected the Chilean average contribution to tax revenue as well as other major macroeconomic variables (see Medina and Soto, 2007, 2016; Pedersen, 2015). Figure 3 highlights these recent trends, as they will turn out useful in our empirical analysis below.

Figure 3: Copper, gold, and bitcoin prices, last 5 years



Source: own elaboration based on www.cochico.cl and www.investing.com.

Chile is the largest producer of copper in the world (Cantallopts, 2016), while boasting the largest reserve at about 200 million tons (Data Sur, 2020). Despite these numbers, and according to some projections, current operations could decrease by 31% in 2031 compared to 2019 (Cochilco, 2020a). This could certainly affect Chile's GDP in the long term, considering that it takes as long as 19 years to build a mining facility (International Monetary Fund, 2021). Table 2 provides more context on the importance of Chilean copper in the international market.

Table 2: Chile's production and reserves of copper and gold, world context

yr. 2021	Production (t)	Reserves (t)	Mcap (USD)
Copper	5,600,000 / 21,000,000 (26%)	200,000,000 / 880,000,000 (23%)	300B
Gold	3.2 / 3,200 (0.1%)	3,700 / 53,000 (7%)	12T

Note: number (tonne) to the left is Chile, to the right is World (Chile's share in parentheses).

Source: U.S. Geological Survey (2022) and Consejo Minero (2021).

In spite of its relative prominence, Chile is not in a position to set the price of copper in the international market. This is likely due to the fact that, currently, most of the copper produced in Chile is sold to China. Indeed, China was the main destination of Chilean exports for copper concentrate in 2020 with 63% of the total, followed by Japan with 17.3% (Cochilco, 2021). It is worth mentioning that China's metals consumption has recently soared and has surpassed the metals consumption of the rest of world in 2015 (see Wang and Wang, 2019). In particular, from 1997 to 2015, China's total metals consumption increased by 3889.35 million tons (see Song et al., 2019).

2.3 Lithium

The white gold, just as the red metal, has many industrial applications, as made clear in Table 3—yet unlike copper, its contribution to Chile's economy is far less striking. Figure 4 shows how small the lithium market is when compared to copper. Thus we see how lithium carbonate, for instance, makes up barely one percent of Chile's export revenues (Luft et al., 2022) and its contribution to Chile's GDP is marginal. However, and considering this metal is a key component in the manufacture of electric vehicles and rechargeable batteries, lithium has stood out as one of the metals with the highest growth in demand in recent years.

As shown in Table 4, Chile remains a relevant producer of lithium and the largest holder in the world—reserves are in the form of brines located in the Atacama Salt Flat (Merino, 2018; Cochilco, 2018; Hersh, 2019; Cochilco, 2020b). Moreover, Chile claimed 51% of the world's reserves in 2020, followed by Australia with 16%, and Argentina with 10% (Cochilco, 2020b).

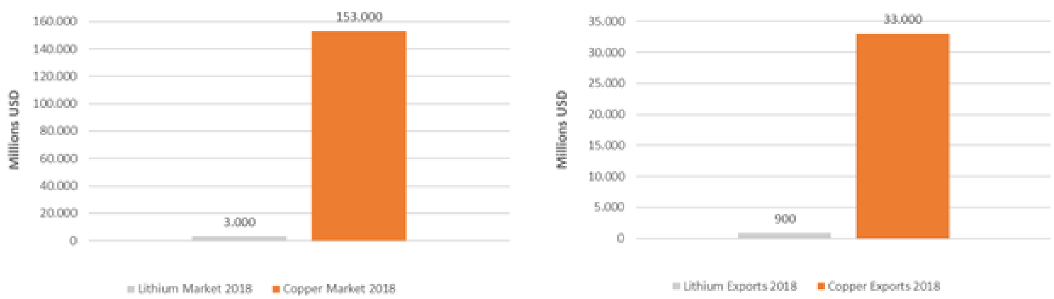
Table 3: Uses and industrial applications of lithium, world

Batteries for EV cars	41%
Batteries for electronic use	16%
Glass and ceramic materials	15%
Energy storage	8%
Lubricant and polish	8%
Others	6%
Metallurgy	3%
Air treatment	3%
	100%

Source: Gonzalez and Cantallopts (2021).

Figure 4: Lithium and Copper compared

In the world markets | In Chile's exports



Source: Merino (2018).

Table 4: Chile's production and reserves of lithium and gold, world context

yr. 2021	Production (t)	Reserves (t)	Mcap (USD)
Lithium	26,000 / 100,000 (26%)	9,200,000 / 22,000,000 (42%)	1.3B
Gold	3.2 / 3,200 (0.1%)	3,700 / 53,000 (7%)	12T

Note: number (tonne) to the left is Chile, to the right is World (Chile's share in parentheses).

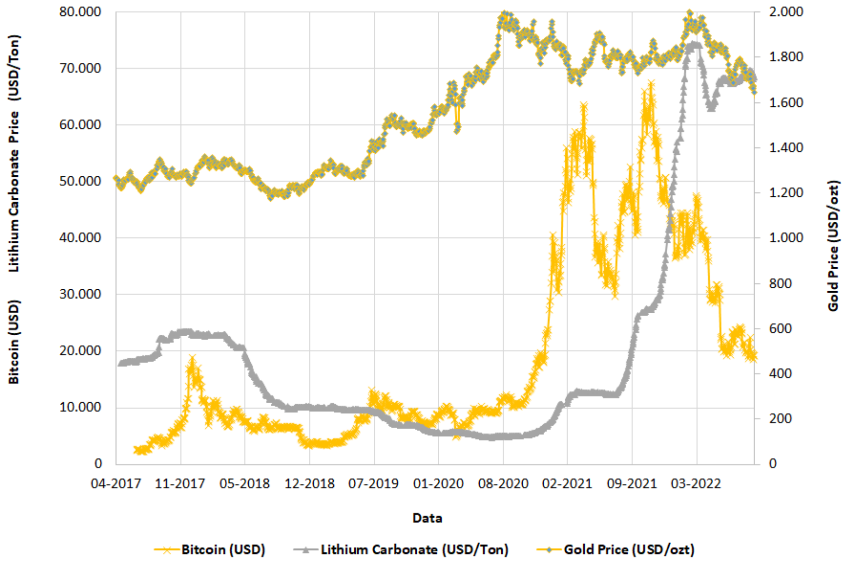
Source: U.S. Geological Survey (2022) and Consejo Minero (2021).

The most important commercial product in the market for Chile is lithium carbonate, far ahead of lithium chloride and hydroxide. Besides, the country is the world's second-largest producer of lithium, after Australia surpassed it in 2017, and it is expected that Argentina will overtake Chile by 2028 (Luft et al., 2022). This could affect the relevance of Chile as producer in the long term, considering that lithium often requires capital-intensive investment and takes as long as 7 years to construct a mining facility (International Monetary Fund, 2021).

The price of lithium has been on the rise over the past 40 years and it has skyrocketed since the second semester of 2021 (Trading Economics, 2022), as highlighted in Figure

5. In addition, lithium prices (carbonate and hydroxide) have probably experienced bubble episodes, particularly from the end of 2015 to the end of 2018, and in the case of European hydroxide, the bubble was felt as recently as September 2020 (see Uribe et al., 2021).

Figure 5: Lithium, gold, and bitcoin prices, last 5 years



Source: own elaboration based on www.cochico.cl and www.investing.com.

Currently, there is a pronounced dominance of lithium technology in Southeast Asia along with a significant share in metal consumption (Zícari et al., 2019). For instance, China concentrated 55% of consumption worldwide, South Korea 20%, and Japan 12% in 2020 (Gonzalez and Cantallopts, 2021). It must be observed that the high level of consumption in China is due to the construction of an industrial chain of manufacture of lithium-ion batteries, which require around 80% of the manufacturing capacity of battery cells.

Now we turn our attention to the potential intersection between transition metals, cryptos, and the underlying technology, the blockchain.

3 Cryptos, blockchain, and transition metals?

The literature on the behavior, volatility, and safe-haven properties of both crypto-assets and precious metals, has recently been rekindled.[4] This is partly due to the

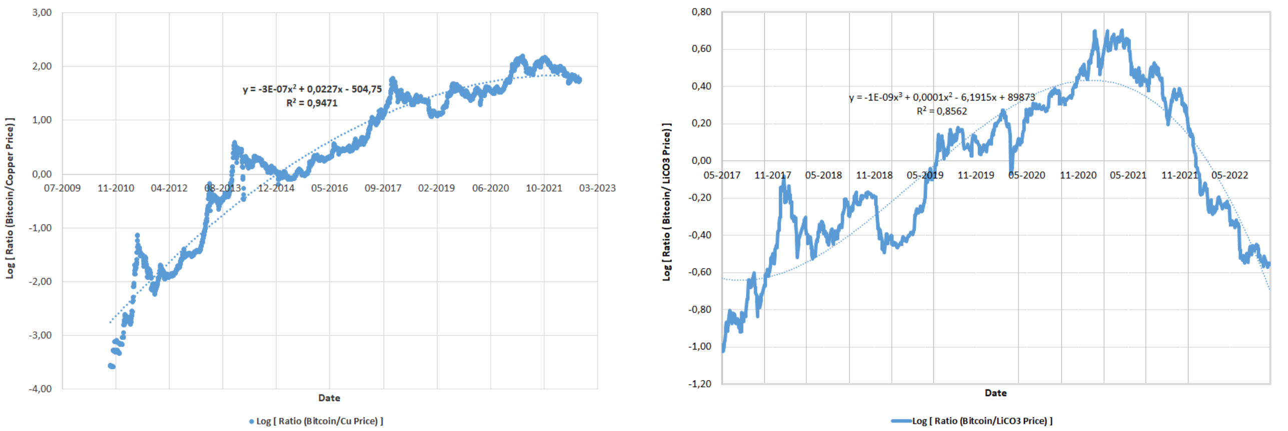
[4]See, among many others, Adekoya et al. (2022); Agnese and Thoss (2021); Bildirici and Sonustun (2022); Doumenis et al. (2021); Elsayed et al. (2021); Erdas (2018); Fasanya et al. (2021); Hassan et al. (2021); Mensi et al. (2018, 2019); Yatie (2022a, 2022b); and Wen et al. (2022).

necessity to address the topic under the light of recent geopolitical events, such as the covid pandemic or the Ukraine war, which have shown a composite effect on global uncertainty. However, critical metals such as copper and lithium have not yet received as much attention.[5] Our intention is to fill this gap, as we think there is a large intersection when it comes to the energy sector.

Figure 6 exhibits the fluctuations over time in the bitcoin-to-copper price and bitcoin-to-LiCO3 price ratios. The trend for both ratios has been upward, including much of the covid period (2020-2021), evidencing that bitcoin appreciated more than copper and lithium. However, for lithium this trend has changed since July 2021, when its price began to rise to historic levels right during the Ukraine war while the bitcoin price dropped considerably. Figure 7 provides further context and shows the evolution of major stock market energy-transition indexes along with Chile's stock market index IPSA.

Figure 6: Bitcoin and transition metals

bitcoin-to-copper | bitcoin-to-LiCO3



Source: own elaboration based on Investing.com.

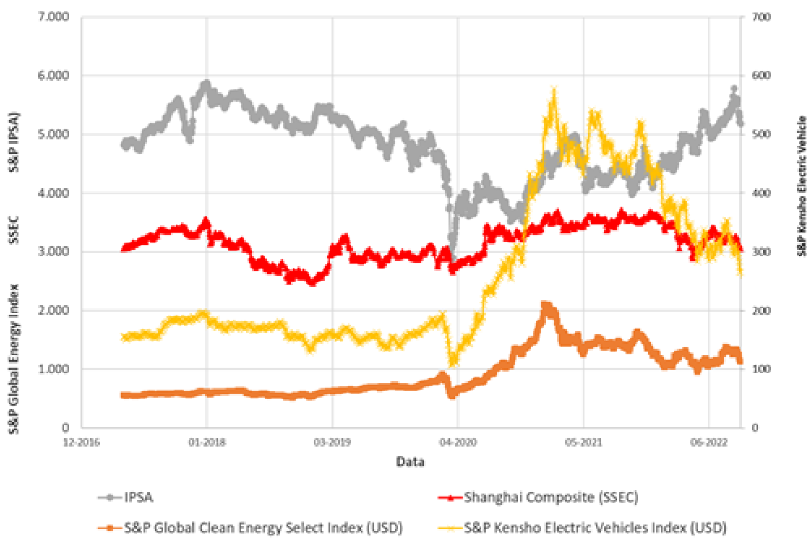
Arguably, covid lockdowns and the war in Ukraine have brought about the collapse of the supply chain—in other words, these commodities have been in high demand while the supply became restricted, thus making for higher commodity and stock prices.

One still puzzling question that emerges in all things crypto is that of energy consumption. According to Halaburda et al. (2020) and Schinckus et al. (2020), bitcoin has generated significant costs in terms of energy because of a considerable volume of commercial transactions worldwide. Energy tracking studies have estimated energy

[5] A critical metal can be defined as a metal that is considered essential for the economy which is also subject to a high risk of supply disruption—these metals are often used in high-tech applications such as electronics, renewable energy systems, and electric vehicles. Notice that the terms critical and transition metals are not interchangeable.

consumption ranges of 29.96 TWh to 135.12 TWh for bitcoin as of July 2021 (Kohli et al., 2022). Table 5 suggests bitcoin mining could consume as much energy as Sweden, but putting things into perspective also shows Google and Facebook consuming considerable amounts at 15.4 TWh (Google, 2022) and 7.1 TWh (Facebook, 2020) respectively for 2020.

Figure 7: Major energy-transition indexes and Chile



Source: own elaboration based on Investing.com and spglobal.com.

On a more positive tone, Sedlmeir et al. (2020) claim that cryptos at large represent no real threat to climate change. Also, Baur and Oll (2021) suggest that it is misleading to focus on the network's absolute carbon emissions or to compare bitcoin's emission to those of entire countries, and that "adding bitcoin to a diversified equity portfolio would reduce the portfolio's aggregate carbon emissions and could enhance the risk–return relationship of the portfolio".

In addition, the major energy concern within the crypto ecosystem is being addressed by the switch, most notably by the ethereum blockchain, from the so-called proof-of-work (PoW) protocol, to the more energy-efficient proof-of-stake (PoS) protocol.

Our empirical section below will address the following question: has any kind of relationship developed between bitcoin and renewable and electromobility-related energies over the past few years? We will try to offer a few intuitions here, before we move to the more technical analysis.

Previous works have examined the relationship between bitcoin and energy commodities like oil, coal, and gas. Rehman and Kang (2021), for instance, found that bitcoin has exhibited a significant correlation with oil and gas over a period of 128–256 days. Moreover, Dogan et al. (2022) found that clean energy and emission allowances are causally associated with bitcoin—in particular, they suggest that bitcoin causes clean energy and carbon allowance.

Table 5: Annual carbon footprint by countries and cryptos

Rank	Country	Population (mill.)	Energy (TWh)	Energy share (%)
0	World	7,878.2	23,398	100.00
1	China	1,444.9	7,500	32.05
2	US	332.9	3,989	17.05
3	India	1,366.4	1,547	6.61
20	Taiwan	23.8	238	1.01
21	Vietnam	98.2	217	0.92
22	South Africa	60.1	210	0.89
23	btc+eth	1.3*	190	0.81
24	Thailand	69.9	186	0.79
25	Poland	37.8	153	0.65
26	Egypt	104.3	151	0.64
27	Malaysia	3.1	147	0.62
28	btc	0.8*	135	0.57
29	Sweden	10.2	132	0.56
49	Switzerland	8.7	56	0.24
50	eth	0.5*	55	0.24
51	Romania	19.1	55	0.23

Source: Kohli et al. (2022). *Rough estimates of active addresses per day (bitinfocharts.com).

On a global perspective, and paradoxically, it is worth highlighting how centralized mining has recently become. China, U.S.A., and Russia, the largest bitcoin mining countries, concentrate around 70% of all the mining, yet also produce most of the renewable energy in the world (see Kohli et al., 2022). In addition, these countries have the largest renewable capacity ratio (RCR), which in turn provides a proportion of the renewable energy available per TWh in bitcoin mining.

According to The Warren Centre at The University of Sydney (2020), it is estimated that all the traditional mining accounts for up to 11% of global energy use. Moreover, even when 94% of all the metal mined in the world is iron, the energy used to extract and process this metal is not so different than copper and gold due to low energy requirements. On the other hand, lithium still has a small production volume with respect to copper or iron, and because of this, the yearly energy to mine it is rather trivial. It is also interesting to note that the world's production of gold is very low with respect to other metals, while its energy requirements are very high because of the low grade of the raw ore—producing only some grams of gold per ore ton.

Hence, if we compare the yearly energy consumption among metals and bitcoin, we would find that the consumption of the latter would be higher than lithium and lower than iron, copper and gold. Likewise, this would also be aligned with other studies suggesting that bitcoin consumes less energy than gold (see Rybarczyk et al., 2021). Table 6 condenses the previous information.

Table 6: Energy consumption to mine metals and bitcoin

Asset	Energy Consumption	Quantity Mined	Estimated consumption (mill. of GJ / year)
Copper	24-27 GJ/Ton Cu*	20,700,000 Ton**	497-559
Lithium	15 GJ/Ton Li*	97,500 Ton**	1.46
Gold	134 x 10^3 - 372 x10^3 GJ/Ton Au*	3,350 Ton**	450-1,246
Iron	0.15-0.30 GJ/Ton Iron ore*	3,040,000,000 Ton**	456-912
Bitcoin	1.08 x 10^8 - 4.86 x10^8 GJ***	19,300,000 BTC	107-486

Source: based on *Allen (2021), **Brown et al. (2021), and ***Kohli et al. (2022).

But is clean energy a safe haven or hedge for cryptocurrencies? Based on crypto's energy consumption levels and the hedge and safe haven properties of a wide range of clean energy indices, Ren and Lucey (2022) suggest clean energy is not a direct hedge for dirty and clean cryptocurrencies, but more likely, it is just for dirty cryptocurrencies during periods of increased uncertainty. It is also worth noting that crypto trading could attract additional resources to develop green technologies for decarbonizing economic growth. For example, Lia and Meng (2022) suggest that renewable energy stocks can be considered as the main spillover contributors in a connectedness system between cryptos and renewable energy stock markets.

On a slightly different note it might be important to tap into the electromobility sector. The impact of Elon Musk's Tesla on the world economy has been widely studied, but not so much in its affair with crypto. Tesla is arguably the most important electric car company in the world, and claims to accelerate the world's transition to sustainable energy with electric cars, solar, and integrated renewable energy solutions. Furthermore, Elon Musk has had a great effect on the price evolution of bitcoin (see Jiang, 2022), and especially so when Tesla stopped accepting bitcoin payments over climate concerns (Bains et al., 2021). It is then no surprise to see proposals emerge on the design of a private bitcoin-based payment network among electric vehicles and charging stations (Erdin et al., 2018).

We conclude this section by arguing that energy is the common denominator among cryptos and the energy transition metals copper and lithium. According to the World Bank (2020), this novel technology, the blockchain, can help companies participate more effectively in the climate market by linking energy and climate sectors, businesses, and customers. For example, since 2020, a blockchain initiative has been running in Chile to support distributed generation transactions and carbon markets in general, as mining companies are currently under increasing pressure to reduce their carbon emissions. Such blockchain-based solution is aimed at monitoring renewable energy, as to have the companies' green credentials all certified and verified by the blockchain. Thus, the National Electricity Coordinator in Chile started a program called Renova, to track each megawatt hour of renewable energy from the time it is generated to the time it is consumed. By recording this data on the blockchain, the goal is to ensure that end users receive the clean energy they have paid for.

Will the blockchain technology eventually play a distinguishing role in Chile's mining industry?. Will the use of renewable energy in productive processes have other unsuspected implications in the future? Considering mining productivity has been decreasing over the past few years, how could the use of blockchain technology affect this trend in the longer term?

We will try to offer a few intuitions on these pertinent questions, after we go over our econometric framework in the next section.

4 Econometric framework

4.1 Identification

Identification is a well-known issue in economics, dealing mostly with model formulation rather than its estimation. According to Sims (1986), 'identification is the interpretation of historically observed variations in data in a way that allows the variations to be used to predict the consequences of an action not yet undertaken'. Simply put, laying out such a structural model is referred to as identification.

In our case for Chile, we postulate a model where the economy can be hit by international shocks stemming from the transition metals international market. Assuming the Chilean economy would anticipate these shocks, and hence react endogenously, then a VAR model might be suitable. We should however establish a certain sequence or chain of events among our variables—in other words, we need to identify the causal relationships among the variables, and expose the purely exogenous shocks with their dynamic effects (e.g. impulse response functions). We believe a Structural VAR (SVAR) model can give us a more nuanced framework of analysis at this point.

In this context, we want to account for all the lagged-spillover effects among the variables under study, thus avoiding erroneous intuitions. So for instance, assuming an external shock, as measured by the S&P Global clean energy index, we would then like to assess the spillover effects on the Chilean transition sector, by gauging the effect on a major transition metal, copper. Likewise, we would like to assess the effects of a shock, as measured by the S&P Kensho index, on the Chilean electromobility sector, by looking into Chile's major sustainable metal, lithium (e.g. LiCO3).

Our SVAR model will have a recursive structure, as typically considered in the literature, with former variables in the ordering of the model being contemporaneously unaffected by the latter variables. For us, the S&P Global clean energy index (and the S&P Kensho index), as a proxy for global activity in the clean energy sector (or electromobility, for the Kensho index), will affect Chinese activity (Shanghai composite index), a major player in these sectors. Both variables, in turn, will likely have an impact on commodity prices (e.g. metals), including bitcoin (BTC), which will be ordered by their marker caps, and through these, on the Chilean economy (S&P IPSA index). Economic theory suggests that this sequence is not likely to take place in the reverse order.

We will be estimating two versions of the same model, one using the renewable energy international market and copper as the triggering mechanisms, and the other one employing the electromobility sector and lithium.

4.2 SVAR

Following Sims (1980) and Hamilton (1994), we suggest a SVAR model as it provides a very flexible framework for analyzing the interdependencies among six macroeconomic variables.[6] We will entertain two such models, highlighting the two major commodities in the Chilean economy: copper and lithium. Such variables include: the S&P Global clean energy index for the 'copper model' (or the S&P Kensho index for lithium), the gold price (USD/toz), the copper price (USD/toz)—or the lithium price (USD/toz)—, the bitcoin price (USD), and the S&P IPSA (Chile)

The model, in vector form, would be:

$$B_0 y_t = k + B_1 y_{t-1} + B_2 y_{t-2} ... + B_p y_{t-p} + u_t \qquad t \in \mathbb{Z} \tag{1}$$

where

$$y_t = (y_1, ..., y_n)'$$
$$u_t = (u_1, ..., u_n)'$$
$$k = (k_1, ..., k_n)'$$

[6] We limit the number of regressors to six, as conventionally done, given that a larger number might result in estimates with a very high variance and of limited practical use.

$$B_0 = \begin{pmatrix} 1 & -\beta_{12}^{(0)} & ... & ... & -\beta_{1n}^{(0)} \\ -\beta_{21}^{(0)} & 1 & & & \\ & & 1 & & \\ & & & 1 & \\ -\beta_{n1}^{(0)} & ... & ... & ... & 1 \end{pmatrix}$$

and y_t is an $(nx1)$ vector of endogenous variables, u_t an $(nx1)$ vector of structural white noise shocks, B_0 is the invertible (nxn) matrix of contemporaneous correlations of our endogenous variables, and B_s the (nxn) matrix of pth parameters. Premultiplying 1 by B_0^{-1} yields the reduced VAR model, which is the estimable version of the structural model, that is:

$$y_t = c + \Phi_1 y_{t-1} + \Phi_2 y_{t-2} ... + \Phi_p y_{t-p} + \varepsilon_t \qquad t \epsilon \mathbb{Z} \tag{2}$$

where

$$\begin{aligned} B_0 B_0^{-1} &= I \\ c &= B_0^{-1} k \\ \Phi_s &= B_0^{-1} B_s \qquad \text{for } s = 1, 2, ..., p \\ \varepsilon_t &= B_0^{-1} u_t \end{aligned}$$

and ε_t an $(nx1)$ vector of white noise forecast errors, and also a linear combination of the structural shocks u_t.

Thus, in practice, getting matrix B_0 will be equivalent to SVAR identification. We will do that by imposing restrictions on B_0 according to economic theory and intuition, and by multiplying the reduced-form VAR by B_0, hence yielding:

$$B_0 y_t = B_0 c + B_0 \Phi_1 y_{t-1} + B_0 \Phi_2 y_{t-2} ... + B_0 \Phi_p y_{t-p} + B_0 \varepsilon_t \qquad t \epsilon \mathbb{Z} \tag{3}$$

where, of course, $B_0 B_0^{-1} B_s = B_s$. Eventually, we can obtain both the structural shocks and parameters.

The number of restrictions to be imposed will depend on the number of variables in the VAR (n), and can be expressed as the difference between the unknown and known elements. This is the minimum number of restrictions, and will be given by $n^2 = n^2 - n + n$,or the unknown elements in B_0 $(n^2 - n)$, plus the unknown variances of u_t (n), minus the known elements in the variance-covariance matrix $E\varepsilon_t \varepsilon_t^{'}$, which will be $\frac{(n^2+n)}{2}$. The number of restrictions will be then at least equal to $\frac{(n^2-n)}{2}$ $\left(\text{or } \frac{n(n-1)}{2}\right)$, and the model will be just identified.

It is customary to assume a recursive scheme in B_0 by imposing $\frac{(n^2-n)}{2}$ restrictions that will yield a lower triangular matrix, known as the Cholesky factorization or decomposition. Following Sims (1992), we will establish a sequence by which, for example, the 'first' variable will not be contemporaneously affected by the other variables, whereas the 'last' variable will not affect the 'previous' variables, also contemporaneously. Additional restrictions can be imposed, yet whether these overidentifying restrictions are valid will have to be tested via an LR test.

Matrix B_0 thus becomes

$$B_0 = \begin{pmatrix} 1 & 0 & ... & ... & 0 \\ -\beta_{21}^{(0)} & 1 & 0 & ... & 0 \\ & & 1 & 0 & 0 \\ & & & 1 & 0 \\ -\beta_{n1}^{(0)} & ... & ... & ... & 1 \end{pmatrix}$$

We move now to assess the effect of the renewable and electromobility world sectors on the Chilean economy, while taking account of all possible synergies and spillover effects.

5 Empirical analysis

5.1 The dataset

All variables in our dataset are expressed in logs and are stationary after first differencing. Therefore, our interpretation of the estimated coefficients below will be that of short-run parameters. Our main focus, however, will be on the more intuitive impulse response functions (IRFs) and variance decomposition analyses. A quick look at Table 7 shows a few stylized facts, namely, a large volatility in bitcoin—as opposed to low volatility in metals—and a virtually zero growth in the international markets of renewable and electromobility energies as well as in Chile in recent years.

We are thus estimating two SVAR models, while focusing on the two major commodities in the Chilean economy: copper and lithium. All variables are endogenous and include: the S&P Global clean energy index for the renewable energy 'copper model' (or the S&P Kensho index for electromobility and lithium model), the Shanghai Composite (SSEC), the gold price (USD/toz), the copper price (USD/toz)—or the lithium price (USD/toz) for the electromobility model—, the bitcoin price (USD), and the S&P IPSA (Chile). The last variable is where our attention will be directed. Further, due to the anomaly of the covid pandemic and the lockdown policies that ensued, we will run our exercises both for the post-covid and pre-covid periods.

Table 7: Summary statistics, daily frequencies (2017-2022)

	ΔSP_clean	ΔSP_elec	$\Delta SSEC$	ΔAU	ΔCU	$\Delta LI3$	ΔBTC	$\Delta IPSA$
Mean	0.049	0.035	-0.001	0.022	0.023	0.096	0.171	0.004
Median	0.000	0.000	0.000	0.000	0.053	0.000	0.186	-0.013
Max.	11.03	10.75	4.95	6.79	5.67	5.91	22.76	9.25
Min.	-12.49	-12.93	-5.27	-5.40	-6.87	-3.26	-49.73	-15.21
Std. dv.	1.59	1.87	0.90	0.80	1.27	0.88	4.89	1.38
Obs.	1,407	1,407	1,407	1,407	1,407	1,407	1,407	1,407

Note: variables in logs and first differences (e.g. growth rates).

Sources: $IPSA$, Banco Central de Chile bcentral.cl; AU & CU, cochilco.cl; $SSEC$, $LI3$, & BTC, investing.com; and SP_clean & SP_elec, spglobal.com.

5.2 Spillover effects of renewable energy

5.2.1 Granger test

Using the Akaike Information Criterion (AIC) we first estimate a reduced-form VAR (4) model, to begin to understand how our variables relate. Table 8 shows, for each equation in the VAR (in columns), the joint significance of each of the other lagged endogenous variables (in rows) in that particular equation—the last row, in turn, exhibits the joint significance of all the other lagged endogenous variables taken together, for that equation.

Table 8: Granger causality test, 'renewable energy' VAR

	Dependent variable in VAR					
Regressors	ΔSP_clean	$\Delta SSEC$	ΔAU	ΔCU	ΔBTC	$\Delta IPSA$
ΔSP_clean		6.01 [0.19]	10.60 [0.03]	9.28 [0.05]	19.71 [0.00]	16.40 [0.00]
$\Delta SSEC$	4.37 [0.36]		2.19 [0.70]	6.98 [0.14]	1.87 [0.76]	1.46 [0.83]
ΔAU	10.38 [0.03]	3.89 [0.42]		7.24 [0.12]	11.73 [0.02]	6.19 [0.19]
ΔCU	12.11 [0.02]	3.89 [0.42]	9.97 [0.04]		1.13 [0.89]	11.01 [0.03]
ΔBTC	13.07 [0.01]	3.51 [0.47]	18.72 [0.00]	16.95 [0.00]		31.71 [0.00]
$\Delta IPSA$	11.29 [0.02]	2.32 [0.68]	6.73 [0.15]	33.8 [0.00]	0.68 [0.95]	
All	69.80 [0.00]	29.88 [0.07]	72.75 [0.00]	74.87 [0.00]	41.33 [0.00]	107.26 [0.00]

Note: χ^2 (Wald) statistics of joint significance of 'other' lagged endogenous in equation; p-values in brackets. N = 239 obs.

In terms of Granger causality it is interesting to note the importance for Chile of the S&P Global clean energy index, copper, and last (but not least) bitcoin. Notice, too, that the variability of all our variables can be accounted for jointly by the other variables in the model, as seen in the last row—with just one exception (Shanghai composite index), the significance level turns out to be 1%. All the variables seem to be endogenously determined, thus justifying the use of VAR modelling.

5.2.2 SVAR estimates

$$\widehat{B_0^{re}} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ \text{-0.13 [0.00]} & 1 & 0 & 0 & 0 & 0 \\ \cdot & \text{-0.14 [0.03]} & 1 & 0 & 0 & 0 \\ \text{-0.10 [0.01]} & \text{-0.24 [0.00]} & \text{-0.18 [0.01]} & 1 & 0 & 0 \\ \text{-0.68 [0.00]} & \cdot & \cdot & \cdot & 1 & 0 \\ \text{-0.26 [0.00]} & \cdot & \text{0.22 [0.03]} & \text{-0.40 [0.00]} & \text{-0.07 [0.00]} & 1 \end{pmatrix}$$

Note: p-values in brackets.

Following Wang and Wang (2019), we set additional restrictions to matrix $\widehat{B_0^{re}}$ when the estimated coefficients of the short-run parameters are not significant at 10%.[7] As seen in its first column, the inverse of $\widehat{B_0^{re}}$ implies positive and highly significant (<1%) contemporaneous effects from the world's clean energy sector on all the variables of the model. Besides, the second column suggests positive and significant effects from China on gold and copper (see Wang and Wang, 2019, in particular). The remaining columns can be similarly analyzed.

Focusing now on Chile, the last row of $\widehat{B_0^{re}}$ indicates positive and highly significant (<1%) contemporaneous effects from the clean energy sector, copper, and bitcoin, and negative from gold.

5.2.3 Impulse response functions

We are particularly interested in the effects on the Chilean economy during covid times. Our IRFs throw some light on these effects, both instantaneous and cumulative, as seen respectively in the first and second rows of Figure 8. It is to note the stark contrast between US-led and China-led shocks, as measured by the S&P Global clean energy index and the Shanghai composite index, respectively. More stringent covid restrictions on international trade have resulted in a damping down of trade flows and an inhibition of shocks coming from the Asian country. Dependent as it is on the Chinese economy, Chile has surprisingly found itself much more affected by US-led shocks.[8] The first two columns in Figure 8 highlight these contrasting effects.

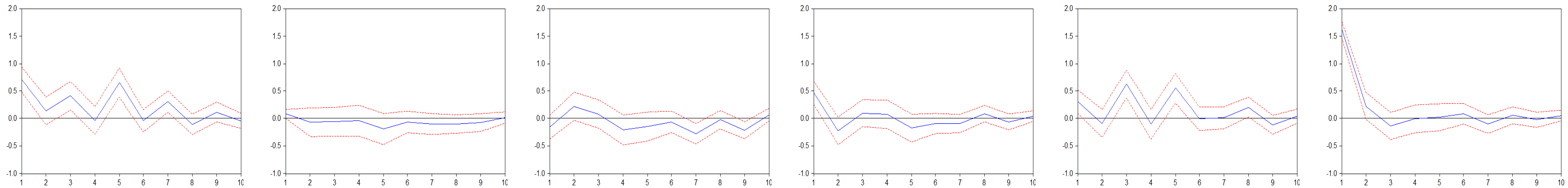
[7] Their model is less restrictive in this regard, at 30% significance.

[8] This is consistent with the results in Wang and Wang (2019).

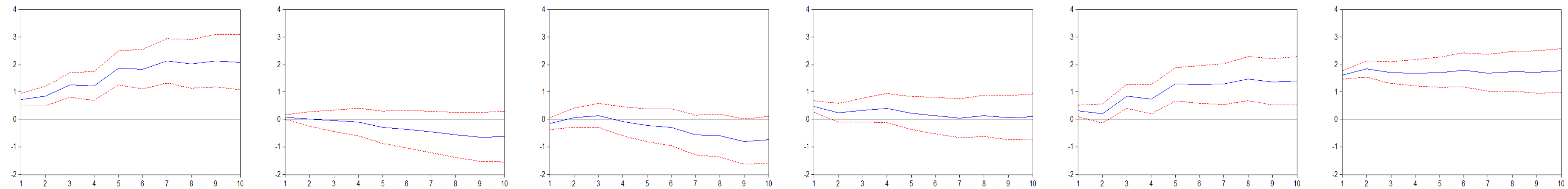
Figure 8: Impulse response functions of Chile's economy to structural shocks (renewable energy)

$\Delta SP\_clean \rightarrow \Delta IPSA$	$\Delta SSEC \rightarrow \Delta IPSA$	$\Delta AU \rightarrow \Delta IPSA$	$\Delta CU \rightarrow \Delta IPSA$	$\Delta BTC \rightarrow \Delta IPSA$	$\Delta IPSA \rightarrow \Delta IPSA$

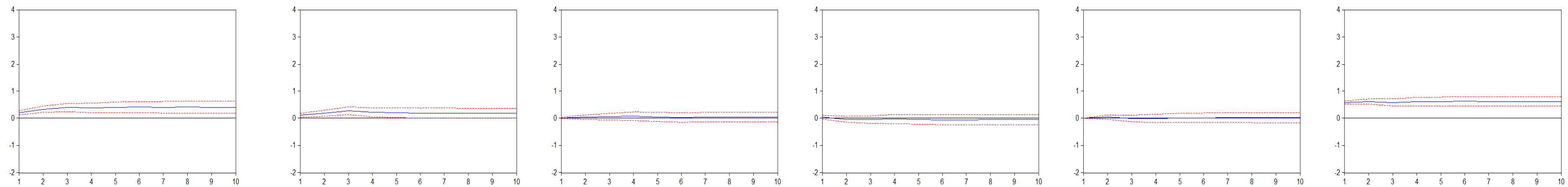
Covid year 2020:



Covid year 2020 (cum.):



Pre-covid year 2018 (cum.):



Note: Responses to structural one standard deviations with $\pm$ 2 standard error bands.

It is also telling how commodities such as gold and copper point to virtually no effect on Chile's economy in the covid context, while bitcoin takes a leading role, possibly due to its 'noncompliance' with traditional finance and regulations. Also, and as suggested above, the concentration of crypto mining, in particular bitcoin, is taking place in accordance with a higher level of renewable energy production. It therefore comes as no surprise to see SP_clean and BTC having the largest cumulative impact on Chile's $IPSA$

Surprisingly enough, when re-estimating the model and calculating the IRFs for pre-covid year 2018, we find virtually no effect on Chile's economy. The 'new normal' has seemingly brought about a whole new dynamics for Chile in relation to the renewable energy sector and bitcoin.

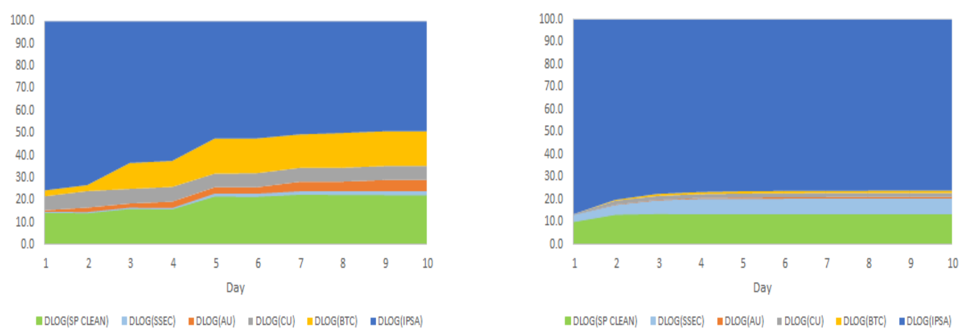
5.2.4 Forecast error variance decomposition

Variance decomposition separates the variation in an endogenous variable into the component shocks to the VAR. As seen in Figure 9, we calculate and plot the contribution of each innovation, current and future, on the forecast error of the $IPSA$ variable.

Consistent with our IRFs, our variance decomposition suggests a growing contribution of US-led shocks in the variability of the Chilean IPSA index (as a measure of economic activity), as opposed to the all but nonexistent Chinese shocks. Moreover, and as expected, copper claims a fair and stable share of the shocks, in tune with Chile's dependence on this renewable energy commodity. As with our IRF analysis, bitcoin shows a growing share of shocks, likely due to the unconstrained nature of this virtual asset—which is arguably something of value in times of financial constraints and capital controls.

Figure 9: Variance decomp. of Chile's economy (renewable)

Covid year 2020 | Pre-covid year 2018



5.3 Spillover effects of electromobility

5.3.1 Granger test

The AIC suggests a VAR (3) model for electromobility and lithium. Table 9 shows, as before, the joint significance of each of the other lagged endogenous variables (in rows) in that particular equation, with the last row being the joint significance of all the other lagged endogenous variables taken together.

Granger test highlights the importance for Chile of the S&P Kensho electromobility index and also bitcoin. With the exception of lithium and bitcoin, all the variables can be jointly explained by the other variables in the VAR. Our results for electromobility should thus be taken with a grain of salt.

Table 9: Granger causality test, 'electromobility' VAR

	Dependent variable in VAR					
Regressors	ΔSP_elec	$\Delta SSEC$	ΔAU	$\Delta LI3$	ΔBTC	$\Delta IPSA$
ΔSP_elec		9.85 [0.02]	1.05 [0.79]	1.05 [0.79]	3.41 [0.33]	18.86 [0.00]
$\Delta SSEC$	2.68 [0.44]		1.24 [0.74]	1.29 [0.73]	1.83 [0.61]	0.87 [0.84]
ΔAU	1.49 [0.68]	4.10 [0.25]		1.81 [0.61]	4.76 [0.19]	4.76 [0.19]
$\Delta LI3$	3.38 [0.34]	6.40 [0.09]	1.01 [0.79]		2.03 [0.56]	3.76 [0.29]
ΔBTC	27.57 [0.00]	7.04 [0.07]	29.33 [0.00]	3.69 [0.29]		22.65 [0.00]
$\Delta IPSA$	0.83 [0.84]	2.61 [0.46]	7.79 [0.05]	3.47 [0.32]	0.28 [0.96]	
All	40.81 [0.00]	35.89 [0.00]	44.09 [0.00]	11.22 [0.74]	16.42 [0.35]	75.76 [0.00]

Note: χ^2 (Wald) statistics of joint significance of 'other' lagged endogenous in equation; p-values in brackets. N = 239 obs.

5.3.2 SVAR estimates

$$\widehat{B_0^{el}} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ \text{-0.06 [0.02]} & 1 & 0 & 0 & 0 & 0 \\ \text{-0.06 [0.02]} & \text{-0.18 [0.01]} & 1 & 0 & 0 & 0 \\ \cdot & \text{-0.07 [0.08]} & \cdot & 1 & 0 & 0 \\ \text{-0.52 [0.00]} & \cdot & \cdot & \text{-1.24 [0.00]} & 1 & 0 \\ \text{-0.15 [0.00]} & \text{-0.23 [0.04]} & \cdot & \cdot & \text{-0.09 [0.00]} & 1 \end{pmatrix}$$

Note: p-values in brackets.

As done for the renewable sector, we set additional restrictions to matrix $\widehat{B_0^{re}}$ when the estimated coefficients of the short-run parameters are not significant at 10%. For instance, the first column shows positive and highly significant (<1%) contemporaneous effects from the world's electromobility sector on the remaining variables of the model, while the second column suggests positive and significant effects from China on gold, lithium, and Chile's economy. The other columns can be similarly analyzed.

Further, the last row of indicates positive and highly significant (<1%) contemporaneous effects on Chile from the electromobility sector, China, and bitcoin.

5.3.3 Impulse response functions

Focusing our attention on Chile and its stock market index $IPSA$ once again, we produce a set of IRFs to assess the spillover effects. Just as before, and in spite of Chile's dependency on the Chinese economy, the South American country has been more affected by US-led shocks.[9] The first two columns in Figure 10 drive the point home yet again. Gold and lithium, in turn, seem to bear no effect on Chile's economy in the covid context, yet bitcoin takes once more a leading role.

Re-estimating the model and calculating the IRFs for pre-covid year 2018 yields no significant effect on Chile's economy. This second exercise should be taken as a robustness check from the previous one above, suggesting that the 'new normal' has created new synergies where energy seems to be a driving force.

5.3.4 Forecast error variance decomposition

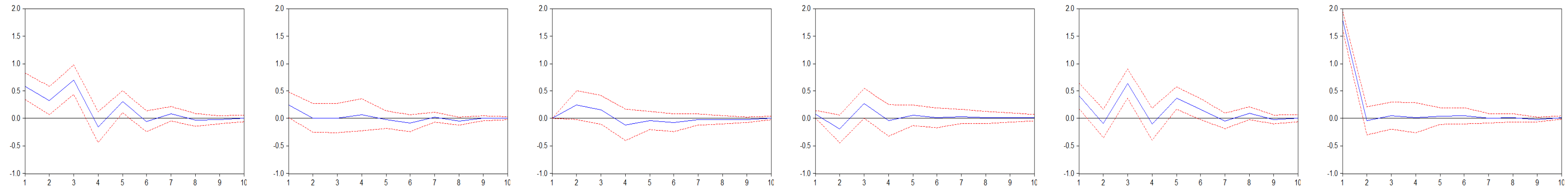
Figure 11 shows again the contribution of each innovation, current and future, on the forecast error of the $IPSA$ variable, taking this time the electromobility model and lithium as references. Results suggests a growing contribution of bitcoin, probably due to its disruptive nature as virtual asset.

[9] See Wang and Wang (2019).

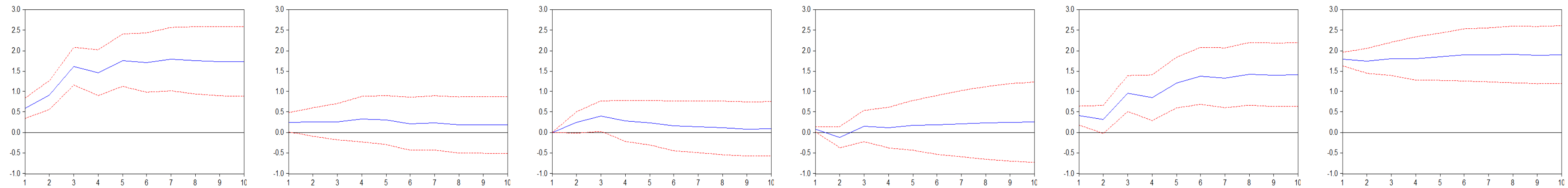
Figure 10: Impulse response functions of Chile's economy to structural shocks (electromobility)

$\Delta SP\_elec \rightarrow \Delta IPSA$	$\Delta SSEC \rightarrow \Delta IPSA$	$\Delta AU \rightarrow \Delta IPSA$	$\Delta LI3 \rightarrow \Delta IPSA$	$\Delta BTC \rightarrow \Delta IPSA$	$\Delta IPSA \rightarrow \Delta IPSA$

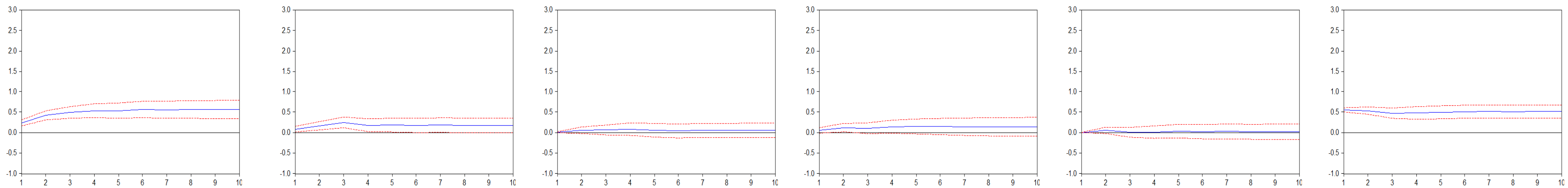
Covid year 2020:



Covid year 2020 (cum.):



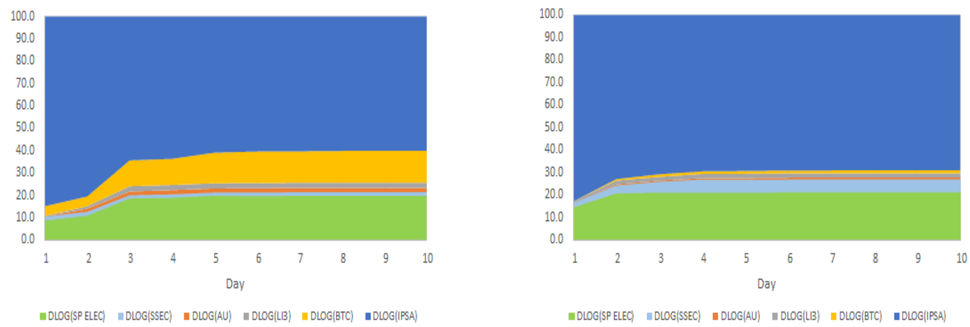
Pre-covid year 2018 (cum.):



Note: Responses to structural one standard deviations with $\pm$ 2 standard error bands.

Figure 11: Variance decomp. of Chile's economy (electrom.)

Covid year 2020	Pre-covid year 2018



6 Conclusions

In this paper we have offered a brief account of the spillover effects of transition metals with a focus on Chile, which remains an important player in international markets. Our approach is innovative in that it introduces a so-far neglected technology, the blockchain, and its counterpart, so-called cryptocurrencies. In particular, we have shown how bitcoin, the most traded of these cryptos, might play a role in the shaping of spillover effects due to international shocks.

With a participation in trade that accounts for more than 65% of its GDP, Chile remains the second most open economy in South America after Paraguay, something that has helped in placing the country in the group of fastest-growing economies in the region. Government authorities are certainly aware of this fact, and should keep working with leading figures in the sector to make the most of this opportunity.

Both our IRFs and variance decomposition analyses seem to suggest very similar results. As a robustness check, we have entertained different indexes representative of different technologies (the S&P Global clean energy index, and the S&P Kensho electromobility index), while putting the stress on the two major transition metals in Chile, copper and lithium.

First off, covid and the new 'inflationary' normal have brought along a new set of rules marked by increased uncertainty and restrictions that are diametrically opposed to the free flow of goods and services in international markets. Second, and likely related to the previous, Chile seems to be more affected by those US-based indexes than by China's SSEC—even when trade with China in recent years has gone from thriving cooperation to an overt dependency. Last, and certainly not least, the blockchain-crypto ecosystem has become more impactful in the development of a metals-based economy like Chile—indeed, this is a timely conclusion as the world is moving to a metals-based economy where demand in general is set to grow in many sectors. It is to notice that for both the US-based indexes and bitcoin our IRFs show a cumulative short-run effect of about 2 percentage points on Chile's IPSA.

Traditionally, and given its initial natural endowments, Chile has had to rely on such metals, particularly copper, to make it to the big markets. It remains to be seen, though, how Chile can cope with this fast transition by also tapping into its vast reserve of lithium. This might prove to be a game changing decision for Chile, in the light of the growing competition from countries like Argentina or Australia, but also a timely adjustment to the expanding demand for a new set of industrial applications, mostly in the construction, energy, and electromobility sectors for copper, and in the electromobility and batteries sectors for lithium. Chile's largest world reserves of copper and lithium will not do the trick on their own, if not accompanied by sensible policy making aimed at trying to add as much value as possible from those multinationals willing to enter the sector.

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