Global Energy Systems and International Trade

by

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Earth and Ocean Sciences
Duke University

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Dissertation submitted in partial fulfillment of
the requirements for the degree of Doctor of Philosophy in the Department of
Earth and Ocean Sciences in the Graduate School
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ABSTRACT

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Abstract

This dissertation is a collection of studies at the intersection of global energy systems and international trade. In the first study (Chapter 2), we estimate the sensitivities of primary energy exports to disruptions through maritime chokepoints. The Strait of Hormuz, which connects the Persian Gulf to the Gulf of Oman, is the conduit between the Persian Gulf region and the rest of the world. The countries in this region are rich in crude oil resources and are major energy exporters. In this study, we apply a two-stage least-squares (2SLS) approach to estimate the impacts of a soft restriction in the Strait of Hormuz to energy exports from the region on a fuel-by-fuel, country-by-country basis. The soft restriction that we evaluate here is maritime piracy, a low-grade but chronic hazard for maritime shipping. Our results suggest that maritime piracy is associated with a 7.5-vessel reduction through the Strait of Hormuz two years after the event occurred. We also find that energy exports from the Persian Gulf are generally resilient to these soft restrictions. The exceptions are refined petroleum products from smaller energy exporters, specifically Bahrain and Kuwait. We find that this is linked to different market structures for refined petroleum products and crude oil. Crude oil is demanded globally, but can only be produced in select regions. Refined petroleum products are also demanded globally, but can be produced where crude oil has been imported.

The second study (Chapter 3) introduces and applies a new hybrid-unit input-output database of energy flows in the global economy. This database, the Hybridized Option for Modeling Input-output Energy Systems (HOMIES), models the financial flows of 26 non-energy sectors and the energy flows of 13 energy types among 136 countries over 20 years (1995-2015). HOMIES is able to trace flows of primary energy (e.g. crude oil), secondary energy (e.g. electricity), and embodied energy. The latter consists of direct energy used to produce a final good and indirect energy incorporated in intermediate goods and services used to make a final product. Using HOMIES, we find that 23% of the world's embodied energy network is comprised of trade linkages in indirect energy between primary energy producing countries and countries with which they do not have direct trade ties. We also find that the global economy is 90% more dependent on imports of indirect energy than direct energy.

The third study (Chapter 4) applies HOMIES to the global supply chains for transport equipment. This sector is unique in its complexity; it requires many kinds of manufacturing inputs from many different countries. It is also a key factor in achieving mobility security, or the ability to meet global transportation demand. The transport equipment sector relies heavily on maritime transport and, consequently, on transit through maritime chokepoints. In this study, we build an extension to HOMIES that isolates the portion of international trade that relies on thirteen key maritime chokepoints. This extension, HOMIES-CP, also differentiates between direct and indirect chokepoint dependence. The former is estimated based on bilateral transactions that require chokepoint transit. The latter compounds chokepoint dependencies as a product or service moves through the supply chain. In this study, we use HOMIES-CP to examine the mechanisms that drive chokepoint dependence in the major exporters and importers of transport equipment.

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The process of writing this dissertation began when I was an undergraduate student taking my first classes in energy and the environment. Throughout the course of my studies, I have been fortunate to have incredibly supportive and expert advisors, including: Mike McElroy, Jean-Francois Mercure, Mark Borsuk, Bas van Ruijven, and Behnam Zakeri. I have also met classmates and colleagues, now close friends, whose own work continues to inspire me each day. I am very lucky to have met and worked alongside these people.

My career in energy systems research would not have been possible without the support of my family. They have always motivated me to keep moving forward, even when things get tough. This dissertation is therefore dedicated to them: my parents Richard and Mariko, my sister Lisa, and my husband Patrick.

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1 Introduction

An enormous amount of energy flows through the global economy. Consider primary energy resources, such as crude oil, natural gas, coal, and uranium. Global exports of these resources totaled 202EJ in 2015 (IEA, 2018a). Given a total primary energy supply (TPES) of 545EJ, this means that almost 40% of energy consumed globally was exported by one country and imported by another (IEA, 2018b). This same year, the ten major primary energy exporters of the world, on average, exported 45% of the energy they produced.[1] The major energy importers of the world imported 42% of the energy they consumed (IEA, 2018a, 2016).[2]

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[1] The ten major exporters include: Russia, Kazakhstan, Canada, Australia, United States, Saudi Arabia, Indonesia, Venezuela, Norway, the Netherlands

[2] The ten major importers include: China, United, States, France, India, Netherlands, Japan, Korea, Germany, United Kingdom, Russia

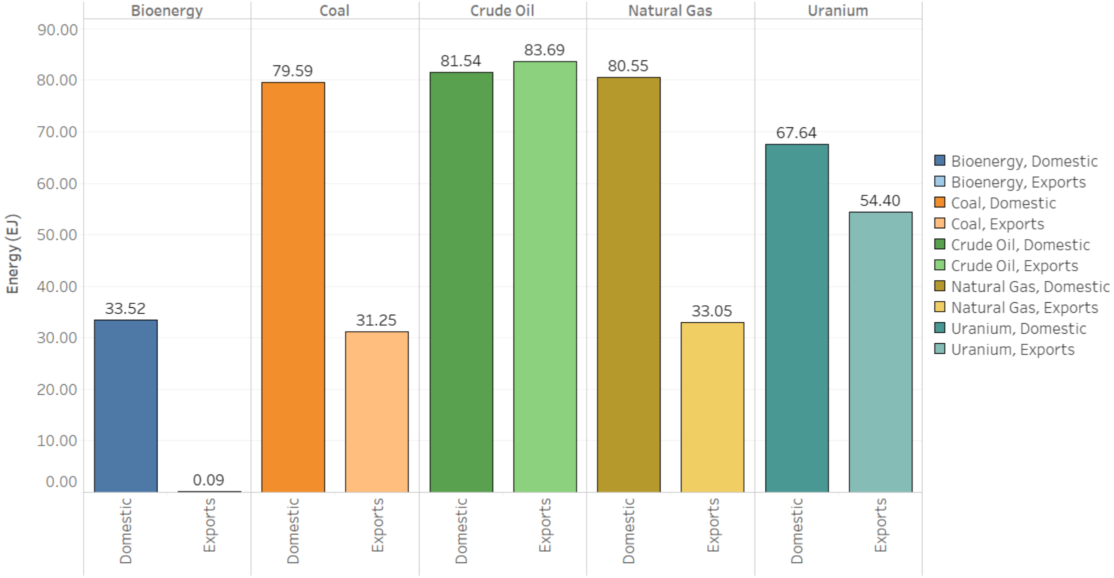

Figure 1. Domestic consumption and exports of primary energy resources (2015). The bars represent the domestic consumption (left, darker hues) and exports (right, lighter hues) of transportable primary energy resources including bioenergy, coal, crude oil, natural gas, and uranium. Primary energy values for uranium exports are estimated by multiplying total trade flows by a constant specific energy for uranium (500MJ/kg) and validating these values using the International Energy Agency's World Energy Balances database. The domestic consumption of uranium is directly derived from the World Energy Balances.

There is also variation by primary energy resource. Crude oil, which is demanded globally but can only be produced in select regions, is largely exported by the countries that produce it (IEA, 2018a). Coal, on the other hand, is expensive to transport and is mainly used domestically (IEA, 2018a). In this way, whether primary energy resources are traded is largely determined by the physical characteristics of the resources themselves.

Most primary energy resources cannot be used directly in their original form.[3] They must be transformed into secondary energy products, such as electricity and refined petroleum. This energy conversion can occur in the countries where the primary energy was first extracted, but often does not (Gary et al., 2007; Simoes and Hidalgo, 2011). For example, Saudi Arabia produced 20.6EJ of crude oil and 2.8EJ of refined petroleum products in 2015. This is because this energy transformation can also occur in energy-importing countries. Japan, which imported 94% of the primary energy it consumed in 2015, refined 1.24 billion barrels that year. This is more than the amount refined by the United Arab Emirates, a major crude oil producer (IEA, 2018a). This adds a level of energy security for primary energy importers, which are dependent on the stability of energy-exporting countries for primary energy but can continue the energy supply chain domestically.

Now consider global supply chains of non-energy goods and services. These supply chains rely on inputs of energy to extract, manufacture, and transport products. They also rely on energy to provide financial, technical, and public services. The total energy requirement to produce a good or render a service is made up by direct and indirect energy flows in the supply chain. Direct energy is used in the final stage of the production process. Indirect energy, on the other hand, is used in the steps leading up to

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[3] The exception here is natural gas, which undergoes processing to remove impurities but does not require refining in the way crude oil does.

the final stage of the process. Say we have a mobile phone. The direct energy requirements would include the electricity used to assemble the phone's components. The indirect energy requirements would include the gasoline required to transport the components, as well as the electricity used to produce the battery, manufacture the conductors, and mine the copper used in the conductors. This electricity also requires a primary energy input for generation.

The use of energy to produce a good or render a service constitutes an energy transformation. This energy is embodied in the output of an economic activity. Energy can therefore be transformed: (i) from primary energy to secondary energy, (ii) from primary energy to indirect energy, (iii) from secondary energy to indirect energy, and (iv) from indirect energy in one activity to indirect energy in another. The total of all these transformation makes up the total energy requirement of a given supply chain. Here, we call this the embodied energy of a good or service.

The various ways in which energy is transformed can complicate how we measure global energy security. Energy security is defined by the International Energy Agency as "…the uninterrupted availability of energy sources at an affordable price" (IEA, 2019). We can evaluate a country's primary energy security by (i) how much it relies on energy imports to meet demand, (ii) the diversity of its energy import portfolio, and (iii) geopolitical, environmental, and economic conditions that can cause volatility and shocks in its energy supply. There are many studies that evaluate the primary energy security of energy-importing countries (Kruyt et al., 2009; Le Coq and Paltseva, 2009; Löschel et al., 2010; Wu et al., 2009) and slightly fewer studies that evaluate the energy security of energy-exporting countries (Löschel et al., 2010; Şen and Babalı, 2007). Generally speaking, the more a country relies on imports of primary energy, the more vulnerable they are to shocks in the energy supply chain (Vivoda, 2009).

Yet energy security is not only based on the movement of energy resources, but also on the movement of energy-intensive economic activities. When the United States exports its manufacturing activity to another country, it is also exporting the energy requirements of this activity. In other words, supply chain logistics can be considered an energy security strategy. Whatever does not need to be produced domestically does not require domestic energy inputs. At the same time, by relying more on energy-intensive activities abroad, a country also relies more on the stability of foreign energy systems. This also has implications for carbon emissions and climate change mitigation. If a country with a low-emitting energy system (e.g. Germany) shifts its manufacturing activity to an emissions-intensive exporter, the supply chain's total emissions will increase (Babiker, 2005). Furthermore, when the country imports manufactured products from the exporter, it is also importing the emissions embedded in them (Chen and Wu, 2017a; Davis and Caldeira, 2010). Globalization is inextricably tied to energy, and understanding the ways in which energy flows through economic systems is crucial in addressing urgent issues like climate change and global energy security.

1.1 The structure of this dissertation

This dissertation is a collection of essays at the intersection of global energy systems and international trade. The first chapter focuses on the implications of disruptions to maritime chokepoints for primary energy security. The second chapter introduces a new input-output (IO) model that traces energy flows through international trade. The third chapter builds on this model with a further methodological development to evaluate the dependence of the global transport equipment sector on maritime chokepoints. All three chapters are linked through energy security, maritime chokepoints, and trade.

In addition, I have included a chapter in the Appendix from my research fellowship at the International Institute of Applied Systems Analysis (IIASA) in the summer of 2019. During this fellowship, I developed a new representation of bilateral trade networks in MESSAGEix, the global energy model built at IIASA. In the study included, we apply this representation to examine scenarios of climate and trade policies on the global energy trade network.

1.2 Maritime chokepoints and energy security

Chokepoints are narrow waterways through which high levels of trade are conducted. Nearly 90% of trade is conducted via maritime routes and primary energy resources are often transported via tankers and barges (UNCTAD, 2018). In this study, we use econometric methods to estimate the impact of transit reductions through the Strait of Hormuz (SOH) on energy exports from the Persian Gulf region. Specifically, we focus on maritime piracy, which represents a soft restriction to maritime chokepoints. A hard restriction, such as a military blockade, impacts all trade. A soft restriction will vary in its impacts to trade based on the product being moved through the chokepoint.

Here, we set out to answer the following questions:

- What is the effect of maritime piracy on vessel transit through the SOH?
- What is the effect of transit reductions on energy exports from the Persian Gulf?
- What drives the heterogeneity in impacts by exporting country and product?

Our hypothesis is that piracy has an impact on traffic through the SOH. This is based on existing literature on maritime piracy and trade, which shows that these relatively chronic low-grade hazards can have significant effects on the cost of conducting trade (Besley et al., 2015). In particular, Bensassi and Martinez-Zarzoso (2012) showed that maritime piracy can have longer term effects; using a gravity model approach, the authors estimated that piracy events are linked to reductions in bulk exports from the European Union to Asia two years after they took place (Bensassi and Martínez-Zarzoso, 2012; Martínez-Zarzoso and Bensassi, 2013a).

In this study, we build on Bensassi and Martinez-Zarzoso (2012) by applying a two-stage least squares approach (2SLS) to our research questions. A 2SLS is a regression in two steps; in the first step, we treat maritime piracy as random shocks and estimate the effect of the piracy on vessel transit through the SOH. In the second step, we take the predicted values from the first step to estimate the impact of vessel transit reductions on energy exports from the Persian Gulf on a country-by-country, fuel-by-fuel basis. In the process, we present a new database of vessel transit through the SOH in which each vessel is linked to the countries that use it most for trade.

The results of this study suggest that an additional piracy event in the SOH is linked to a 7.5-vessel reduction in tanker traffic through the chokepoint two years later. We also find that energy exports from the region are generally not sensitive to this reduction. The exceptions are refined petroleum products (RPP), from small energy exporters like Bahrain and Kuwait. These countries represent a small fraction of the region's energy exports, but their exports comprise a large share of their GDPs. Our results reflect the different market structures of primary energy resources mentioned earlier in this introduction. Crude oil is a universally demanded product that can only be produced in select regions, whereas RPP can be produced in energy-importing countries as well.

1.3 Embodied energy flows through international trade

The third chapter of this dissertation introduces a model and database that traces embodied energy flows through the global economy. As discussed earlier in this chapter, energy flows in a supply chain can be direct (e.g. the energy used to assemble a phone) or indirect (e.g. the energy used to produce the battery or provide financial services). The embodied energy requirement of a sector or country is the total of all direct and indirect flows.

IO analysis (IOA) has been used extensively in economics and industrial ecology to measure the total financial and material requirements of an economic system (Miller and Blair, 2009). Environmentally-extended IOA (EEIOA) builds on the IO literature by measuring the environmental impacts of economic activities through metrics like a carbon footprint (Hendrickson et al., 2006; Lenzen et al., 2012a). EEIOA has conventionally relied on what we define as the direct input-output framework (DIO). In DIO, financial flows of an economic system are modeled first, after which a vector of energy (or emissions) intensities is applied. Studies that employ DIO have found that net exporters of carbon emissions are the countries that have emissions-intensive manufacturing sectors (i.e. China), and that net importers are those countries that import the output of these sectors (i.e. United States and European countries) (Chen and Wu, 2017b; Davis and Caldeira, 2010).

Despite recent methodological advancements in DIO, the approach still suffers from three key drawbacks:

1. *Source assumption:* DIO assumes energy flows start where primary energy is first consumed, rather than where it is first produced/extracted

2. *Proportionality assumption:* DIO, by multiplying an energy intensity vector ex-post, assumes that energy prices are constant across sectors

3. *Unidirectional energy flows:* While DIO captures the flows of energy into non-energy sectors, it does not capture the flows of non-energy output (e.g. steel from steel manufacturing) into energy sectors. In other words, energy is modeled exogenously.

The first drawback is the reason past studies have attributed net energy exports to manufacturing-intensive countries and net energy imports to the countries that import this manufacturing output. In the context of carbon emissions, this is appropriate; emissions should be attributed to the countries where primary energy undergoes combustion. However, in the context of energy security, this limits the boundaries of the energy system. By starting with the energy-consuming country, we leave primary energy exporters out of our evaluations of global energy security.

In this chapter, we introduce an IO database of financial and energy flows that applies a hybrid input-output framework (HIO). In HIO, physical energy flows and financial flows are modeled simultaneously. HIO also represents energy flows from the point of energy production, rather than the point of consumption. The database is named the Hybridized Option for Modeling Input-output Energy Systems (HOMIES). HOMIES traces the financial and energy flows of 136 countries, 26 non-energy sectors (e.g. electronics manufacturing), 13 energy resources, across 20 years (1995-2015). HOMIES follows energy resources as they undergo the four transformations described above. In other words, we can observe primary energy (e.g. natural gas) as it is exported, transformed into secondary energy (e.g. electricity), and used to manufacture a good or render a service (e.g. produce textiles).

In this chapter, we use HOMIES to answer the following questions:

- How are direct energy and indirect energy used?
- In which areas, geographic and economic, do these uses diverge?
- How does our understanding of global energy security change when we map energy flows from their sources to their sinks?

The results of our analysis first illustrate that the production sources of embodied energy are not countries with energy-intensive industries, but countries that initially supply the primary energy used for manufacturing. Importantly, there exist implicit energy linkages between primary energy producers and importers of goods and services. Implicit energy linkages form when two countries do not directly trade energy with each other, but are linked via an intermediary node that uses energy from the primary energy producer to manufacture a product. When a country imports this product, it also imports the indirect primary energy from the original producer. We find that 23% of the world's embodied energy network is comprised of these implicit linkages. After running additional analyses on energy security, we find that current evaluations of global energy security are incomplete because they do not address indirect energy flows that begin where primary energy is first produced.

1.4 Chokepoint dependence and mobility security

In the fourth chapter of this dissertation, we apply HOMIES to understand the dependence of the global transport equipment sector (TE) on maritime chokepoints. TE is one of the most valuable and globalized supply chains in the global economy (Gaulier and Zignago, 2008). In 2015 (the most recent year in HOMIES), the sector represented 12% of the total value of traded goods and services. TE is a critical industry, not only because it provides a means for transportation services, but also because it demands a wide range of manufacturing inputs from a wide range of countries. TE is also a relatively export and import-dependent sector; a quarter of all manufacturing inputs to TE were imported and nearly a quarter of all TE output was ultimately exported (Hausmann et al., 2019).

Recall that roughly 90% of trade is conducted via maritime routes. TE relies heavily on the coordination of global supply chains, which means that it also depends on maritime routes for shipping. In this study, we examine the major exporters and importers of TE equipment to identify the areas in the TE supply chain where chokepoint dependence is greatest. To this end, we ask the following two questions:

- How dependent are TE exporters on key maritime chokepoints?
- How dependent are TE importers on key maritime chokepoints?

These two questions are deceptively complex. TE importers may depend on chokepoints to receive their TE imports. TE exporters may depend on chokepoints to distribute their TE output. Both TE importers and TE exporters' chokepoint dependences increase if the inputs to TE manufacturing also require chokepoint transit. Yet these mechanisms still only describe direct chokepoint dependence. If the supply chains for manufacturing inputs to the TE sector also require chokepoint transit, the TE supply chain is indirectly dependent on that chokepoint. For example, say Saudi Arabia exports crude oil to India, requiring transit through the Strait of Hormuz. India then exports electronics to Japan for Japan to use in TE manufacturing, requiring transit through the Malacca Strait. If India uses some of its imported crude oil in its electronics supply chain, this means that Japan's TE sector is directly dependent on the Malacca Strait and indirectly dependent on the Strait of Hormuz.

In this study, we use HOMIES to address these various processes underlying the chokepoint dependence of the TE supply chain. In doing so, we make a methodological development to the IO framework. This development, which we call the HOMIES-CP extension (CP = chokepoint), estimates the total value of trade transiting chokepoints to meet TE demand. Existing studies on chokepoints and their associated risks to trade have focused on energy security (Komiss and Huntzinger, 2011; Rodrigue, 2004a) and food security (Wellesley et al., 2017). This study is the first to evaluate chokepoint dependence in the context of mobility security, which we define here as the ability to meet the global demand for transport equipment.

Our results suggest that for TE exporters, chokepoint dependence is based on a tension between economic growth and transitions in sectoral interactions, as well as a shift in production from domestic systems to foreign systems. For importers, the clearest trend is the shift in TE supply chain from more local regions to China. For the largest importers of TE, there is a clear increase in the dependence on the South and East China Seas. These metrics provide a measure of vulnerability in the TE supply chain and provides one dimension of overall risk. The global demand for transportation is projected to grow three-fold by 2050 (OECD, 2019). By examining the chokepoint dependencies of major TE importers and exporters, we can identify the economic characteristics that may exacerbate risks to mobility security in the future.

2 Maritime piracy in the Strait of Hormuz and implications of energy export security

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2.1 Introduction

Fossil fuels comprised 81% of primary energy consumption in 2016 (International Energy Agency, 2018a). In this same year, Persian Gulf Countries (PGCs), i.e. Bahrain, Iran, Iraq, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates (UAE), supplied 32% of the world's crude oil production and 27% of all hydrocarbon exports, including crude oil (~44%), refined petroleum products (~14%) and natural gas (~15%) (Gaulier and Zignago, 2008; IEA, 2018a; OPEC, 2018)[1]. Income from these fuel exports constituted 6-30% of each PGC's Gross Domestic Product (GDP).[2]

The vast majority of fuel exports originating from PGCs are transported to the rest of the world by tanker vessels that have to pass through the Strait of Hormuz (SOH), the only maritime passageway into and out of the Persian Gulf. There are alternative outlets for PGC crude oil, such as pipelines and other ports away from the Persian Gulf, but the export capacity of these alternatives is limited and relatively small

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[1] Author's calculations based on data from the IEA World Balances, OPEC Statistical Bulletin, and CEPII BACI bilateral trade database.

[2] Authors' calculations based on GDP data from the World Bank and the BACI bilateral trade database.

compared to that of shipping. In 2018, tankers moving through the SOH carried 35% of all maritime trade in oil that year (EIA, 2018). And since oil overwhelmingly remains the primary energy source from which transportation fuels are derived, the heavy reliance of shipping on the SOH makes it the most important marine constriction, or chokepoint, through which global trade moves (Barden, 2019; EIA, 2018).

Fuel exports passing through the SOH have historically faced significant threats stemming from geopolitics and international conflict. These threats are rooted in political interests formed at the turn of the 20th century (Owen, 2008); here we speak on the last 50 years. The "Surrogate Strategy" applied by the United States in 1971 aimed to preserve Western energy interests by strengthening Iran, Saudi Arabia, and Israel through military assistance (Şen and Babali, 2007). This preferential outside support of some PGCs over others started a power rivalry in the region that continues to this day, and has left trade through the SOH vulnerable to disruption due to increasing conflict and armament of the region. For example, during the Iran-Iraq War (1980-1988), also known as the "Tanker War" (1984-1988), both combatant and non-combatant vessels transiting the chokepoint were attacked (O'Rourke, 1988). And during the First Gulf War (1990-1991), which was triggered by a dispute over ownership of a large oil field located between Iraq and Kuwait, threats to tankers carrying these countries' fuel exports resulted in a near-doubling of global oil prices (Talmadge, 2008). Furthermore, Iran has and continues to threaten shipping through the SOH, with its seizure of the

British oil tanker Steno Impero being the most recent example (BBC, 2019; Faucon and Rasmussen, 2019).

In addition to these geopolitical security risks, shipping through the SOH also faces security risks due to theft and extortion. A principal example of this type of risk is maritime piracy, which is unique among threats to shipping using the SOH because 1) it largely occurs in international waters, 2) the piracy attacks are generally not carried out by state actors, and 3) there is no single body responsible for policing piracy (Middleton, 2008). Between 2008 and 2011, piracy largely originating from Somalia spiked in the Arabian Sea outside the SOH, prompting the international community to recognize maritime piracy as a chronic threat to international trade stemming from long-term institutional failures (Knops, 2012). For instance, the spike in Somali piracy is attributed to droughts and subsequent economic conflict in Somalia (Ploch et al., 2011; Silva, 2010). It has been noted that these kinds of failures can reduce trade more than independent tariff policies (Anderson and Marcouiller, 2002). International policing of the Arabian Sea has since reduced piracy attacks in the region, though attacks have started to rise again in recent years (International Maritime Bureau, 2018).

Short-term costs of maritime piracy to international trade can be significant. Using a difference-in-differences regression approach comparing trade flows requiring transit through high-piracy areas with those that do not, Besley et al. (2015) find that the increase in Arabian Sea piracy attacks in 2008 led to an 8-12% increase in the cost of shipping dry bulk goods. The authors argue that this increase is largely driven by higher insurance and security costs (Besley et al., 2015). Studies have also examined the longer term effects of piracy on trade. For instance, Bensassi and Martinez-Zarzoso (2012) showed that piracy affects overall international trade years after attacks. These authors focused on bulk exports from the European Union to Asia from 1999 to 2008 and directly included lagged piracy attacks in a gravity model to account for additional trade frictions likely caused by these events. Doing this, the authors found that an additional 10 attacks are associated with an 11% decrease in total exports (Bensassi and Martínez-Zarzoso, 2012).

In the context of energy security, Wu et al. (2009) argue that piracy poses a large threat to Chinese crude oil imports. The authors base this on the share of imports requiring transit through areas prone to attacks, but do not estimate this risk statistically (Wu et al., 2009). Dinwoodie et al. (2013) use survey methodologies to find that re-routing to avoid high-piracy areas may increase the voyage length of energy commodities by 5% (Dinwoodie et al., 2013). Bendall (2010) uses a scenario analysis in which all trade transiting the Suez Canal is rerouted through the Cape of Good Hope (Bendall, 2010). Fu et al. (2010) follow a similar approach but model a 10% transfer of trade (Fu et al., 2010). Both studies find that piracy can increase the cost of international shipping significantly through increased voyage length and fuel costs.

In the SOH, piracy represents what we define as a *soft* restriction on trade. This is in contrast to a *hard* restriction that may come in the form of a military blockade. Whereas a hard restriction impacts all trade, the impact of a soft restriction on trade may be dependent on the type of good. For example, because the PGC account for more than 30% of global crude oil production and 50% of global crude oil reserves (U.S. Energy Information Administration, 2019a), the global oil market has historically been considered an oligopoly led by the PGC. Other fuel products produced by the PGC, however, such as refined petroleum products (RPP), are traded in a much more competitive market (Gary et al., 2007). This is because while RPP prices correlate with crude oil prices, they are refined from crude oil not just in the PGC but in countries throughout the world.[3] In fact, the top RPP-exporting region in 2017 was not the PGC but Europe (Simoes and Hidalgo, 2011). As a result, soft restrictions such as piracy may have a different impact on PGC exports of RPP than on their exports of crude oil.

We test this idea in this study by examining the degree to which specific energy exports from the PGC are affected by maritime piracy. We do this by assessing whether piracy attacks near the SOH have reduced shipping through the SOH, and if so, then estimate the effect of the reduction on PGC energy exports on a country-by-country and fuel-by-fuel basis. The methods we employ build on such earlier work as Feyrer (2009)

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[3] We note here that the existing literature confirms that refined petroleum prices respond asymmetrically to crude oil prices (i.e. they respond quicker to increases in crude oil price than to decreases) (Atil et al., 2014; Borenstein et al., 1997).

and Hugot and Dajud (2017) who, using the Suez Canal Crisis as a natural experiment, statistically showed the importance of sea distance on trade, also referred to as the "distance elasticity of trade" (Feyrer, 2009; Hugot and Dajud, 2017).

A simple regression of trade volumes on vessel transit suffers from endogeneity due to simultaneous causality; while increased increased vessel traffic can increase fuel exports, an increase in fuel exports can also increase vessel traffic. To mitigate this endogeneity, we use a two-stage least squares (2SLS) methodology. In the first stage, vessel traffic through the SOH is regressed against lagged piracy attacks to determine the degree to which shipping may have been reduced 1-2 years after the attacks (Bensassi and Martínez-Zarzoso, 2012). Then, in the second stage, we use any statistically significant reductions to estimate what these could cost the PGC based on impacts to bilateral trade flows. We have compiled a novel database for this study linking vessel-level transit data through the SOH with publicly available bilateral trade data. As part of this data compilation, we introduce a methodology for linking vessels to the countries that use them by tracking the vessels as they enter shipping ports of call.

Based on our results, we find that an additional piracy attack in the vicinity of the SOH correlates with a 7.5-vessel reduction in tanker traffic through the Strait two years after an attack. Our results indicate that PGC exports of crude oil are not sensitive to these soft restrictions. However, RPP exports are sensitive, at least for Kuwait and Bahrain, countries whose quantity of energy exports are among the smallest in the PGC, but for whom the exports yield a large fraction of these nations' GDP. The findings for Kuwait are particularly relevant in this regard because the country exports both RPP and crude oil, yet in our analysis, it is only Kuwait's RPP exports that are affected by piracy. This suggests that exports of crude oil through the SOH are more resilient to soft restrictions due, at least in part, to the oligopolistic nature of the global crude oil market in which buyers of crude oil have few other sellers. RPP exhibit sensitivity because buyers in this competitive market have many more options in terms of their energy exporter.

2.2 Data

2.2.1 Piracy in the Strait of Hormuz

The piracy events used for this analysis span from 2000 to 2016 and come from annual reports published by the International Maritime Bureau (IMB) and the International Maritime Organization (IMO).[4] Each report includes information on the vessel attacked (IMO identifier, flag, DWT), the date the attack occurred, and information on conditions during the attack (e.g. number of crew members, whether the attack was successful). We combine these data using the vessel's IMO identifier and the date it was attacked assuming that the same vessel cannot be hijacked twice in one day

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[4] We use text-parsing programs to transfer IMB annual reports (PDF) into datasets. IMO reports are provided in CSV format.

(*n* = 5,612).[5] For the purposes of this analysis, we include all types of attack (e.g. boarded, hijacked, and attempted).

Geographic coordinates of where the attack occurred are available for 59.2% of the observations in the combined dataset. The 40% of events lacking these data include the name of the closest country to the attack. We assign an attack as having occurred in the SOH if, 1) the incident is directly labeled as having occurred in the SOH, 2) the incident occurred off of Bahrain, Iran, Iraq, Kuwait, Oman, Qatar, or the United Arab Emirates, or 3) the geographical coordinates are such that the latitude falls between 15 and 30 degrees and the longitude falls between 45 and 60 degrees.

These data enable us to assign indicators for whether a piracy attack occurred in the SOH for 93.5% of the piracy sample. Attacks in the SOH accounted for 3.8% of all attacks between 2000 and 2016. Figure 2 illustrates trends in these attacks, differentiated by whether the attacks was "attempted" or "successful". In this study, an attack includes any piracy-related incident.

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[5] We allow for this assumption so that we can link datasets at the vessel-date level, instead of at the vessel-date-attack level.

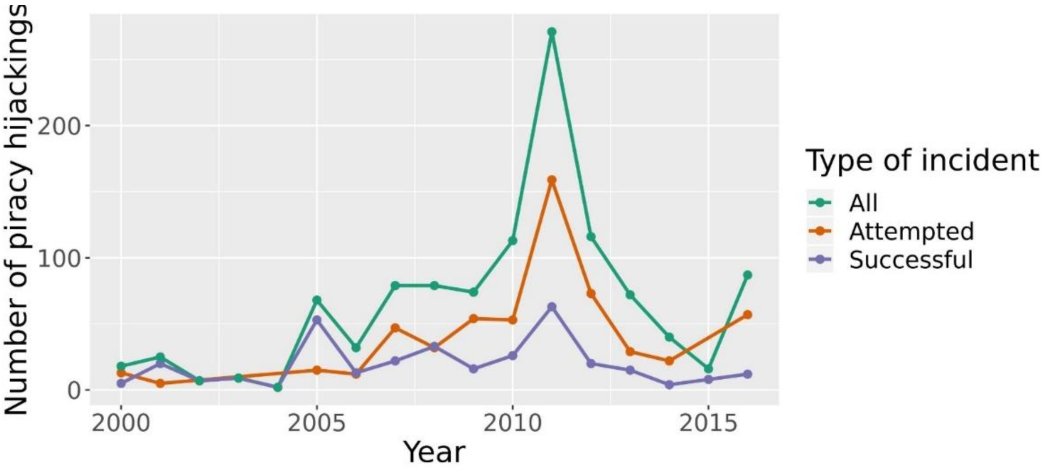

Figure 2. Number of piracy incidents in the Strait of Hormuz (SOH) between 2000 and 2016. "All" incidents include both attempted and successful attacks, as well as a small number of uncategorized incidents. Data are derived from the International Maritime Bureau (IMB) and International Maritime Organization (IMO), with authors' calculations.

2.2.2 Vessel traffic through the Strait

Data on vessel traffic through the SOH was obtained through a paid subscription to Lloyd's List Intelligence *Seasearcher*. This platform provides Automatic Identification System (AIS) transponder records of the transit positions for all vessels registered with the IMO. The data we worked with was limited to vessels whose AIS transponders were captured by a centrally-located sensor in the SOH. This dataset consisted of 162,237 vessel transits between 2010 and 2016.[6] The IMO identifier associated with each ship record also allowed us to identify the ship type. A range of vessel types were included in

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[6] These data, combined with a panel dataset of trade variables, allows us to extract causal effect with statistical power.

the AIS data. Here we focus on tankers, which are used to transport fuels. Figure 3 illustrates the trends in both piracy and vessel traffic through the SOH during the period of this analysis.

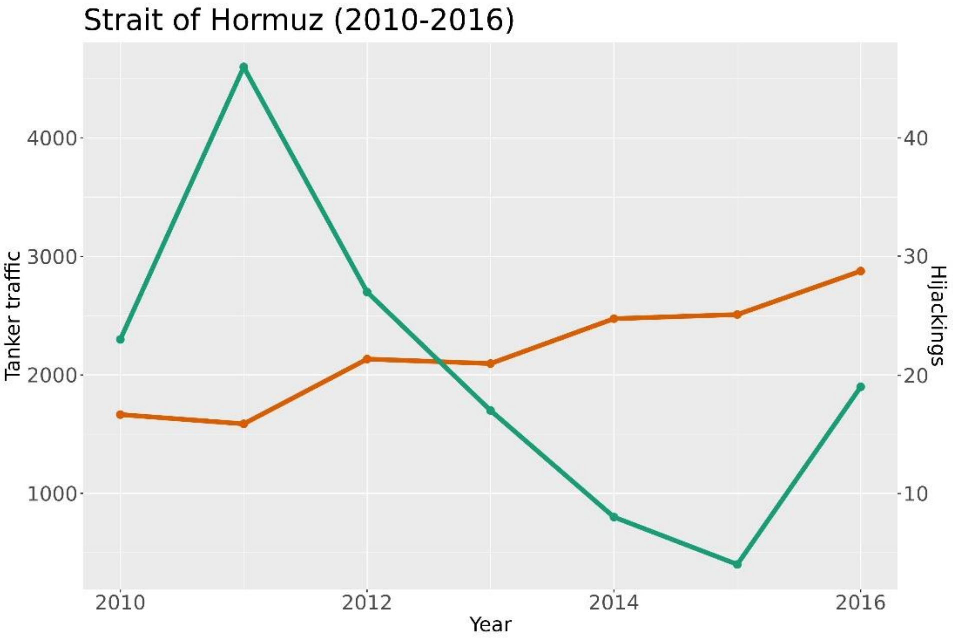

Figure 3. Tanker traffic and attacks in and around the Strait of Hormuz (SOH). Tanker traffic is in orange; attacks are in green. Each observation when counting vessel traffic represents a vessel-date. We assume that a vessel can only transit a chokepoint once per date, and that no vessel can be hijacked more than once per date. We make this assumption to link data at the vessel-date level without duplicates. Total vessel traffic reflects all vessel movements in and around each Strait and is not limited to vessels moving directly to and from a GCC. Here we only present tanker traffic through the SOH.

This figure does not illustrate the country-level variation, which we tease out using regression analysis.

2.2.3 Linking vessel traffic and piracy incidents to countries

We treat piracy events as being random; i.e. they do not preferentially target trade involving particular countries. While a prior study on the randomness of piracy concluded that attacks are not random by flag, the country that a vessel is flagged under is generally not the exporter or importer of the good(s) the vessel is carrying (Mejia et al., 2009). Figure 4(a) illustrates the distribution of vessels transiting the SOH by flag.

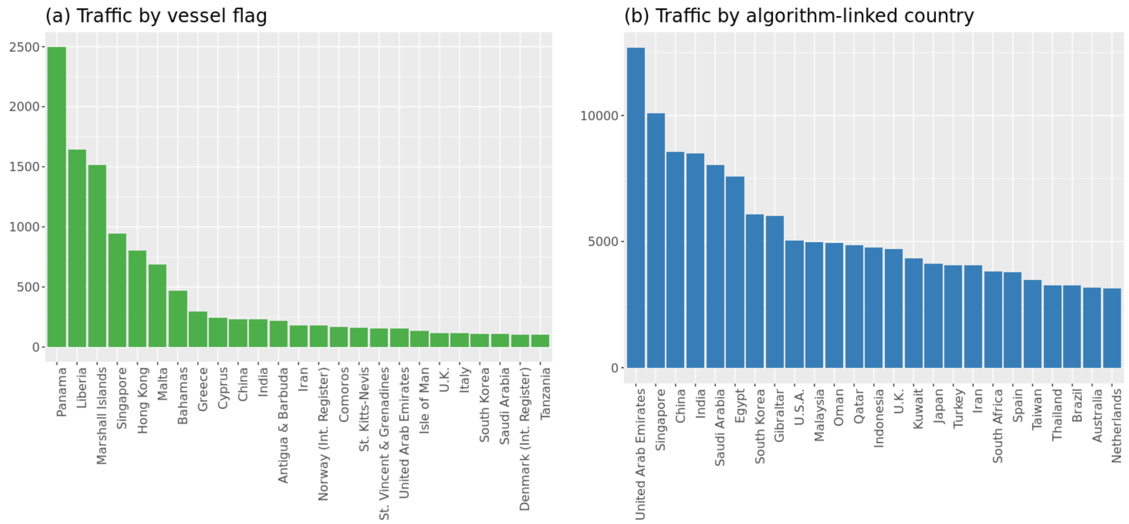

Figure 4. Distribution of vessels transiting the SOH. The illustration shows distributions (a) by flag and (b) by algorithm-linked country. All vessels that transit the SOH during the period of this analysis (2010-2016) are included.

These countries are likely not those that use the vessels for their own trade; Panama, Liberia, and the Marshall Islands, for example, are not the major players transiting the SOH. Thus, an analysis of maritime trade requires the accurate association of vessels with the countries the vessels move between. We do this by applying a vessel-linking algorithm that traces each vessel's movements six months before and after transiting the SOH. This algorithm generates a distribution of port entries that link the vessel to the countries to which it moves the most. While the first port of call presents a possible alternative for assigning vessels to countries, vessels often enter intermediate ports prior to reaching their destination. These intermediate ports may not represent the importing nations. We therefore base vessel assignments to countries on the frequency of port entries over an extended period of time.

We run tests of randomization on the algorithm-linked data and find that attacks are, in fact, random with respect to the countries associated with each vessel. Figure 4(b) illustrates the distribution of vessels transiting the SOH by algorithm-linked country. Detailed explanations of the algorithm and the randomization test can be found in Section S4-S6 of the Supplementary Material.

2.2.4 Bilateral fuel trade data

PGC trade in fossil fuels comes from the BACI trade database (Gaulier and Zignago, 2008). This database identifies importer, exporter, year, product, product amount and trade nominal value, and is tabulated by the harmonized system (HS) 6-digit code (n = 79,233,428). We subset these data to only include records of trades involving the PGC in fuels (n = 204,978).

Fluctuations in shipping through the SOH can be both a driver of changes in trade (e.g., through changes in transportation costs) as well as a response to changes in trade (e.g., through changes in import demand of shipped products). Therefore, year-on-year differences in shipping are endogenous and cannot be used to directly disentangle market-driven impacts on PGC exports/imports from impacts caused by non-market risks to international shipping (Jacks and Pendakur, 2010). We overcome this complication by using a 2SLS. The first stage of the regression estimates how much shipping through each Strait was reduced as a result of past individual piracy events. Predicted traffic from the first stage is then used as the principal independent variable in the second stage of the regression to estimate any corresponding change in the tonnage and value of PGC fuel exports. It is important to note that while we base the first stage regression on the vessel transit and piracy datasets, we do not use these data to proxy for bilateral imports and exports in the second stage. The second stage is based on actual values of bilateral trade derived from the BACI database.

2.3 Methodology

The goal of this analysis is to calculate the effect of a one vessel decrease in strait traffic on energy exports by PGC. Ideally, in a world with perfect information, this model would be estimated using the following regression formula.[7]

$$Y_{ijkt} = \alpha_0 + \lambda_1 T_{it} + \lambda_{2,j}\boldsymbol{\Phi_j} + \lambda_{3,t}\boldsymbol{\Lambda_t} + \epsilon_{ijkt}$$

[Equation 2.1]

Where Y_{ijkt} is exports of energy product k from PGC i to country j in year t; T_{it} is strait traffic through the SOH associated with PGC i in year t; and ϵ_{ijkt} is the residual associated with the model. The formula also includes country-level fixed effects ($\boldsymbol{\Phi_j}$) and year fixed effects ($\boldsymbol{\Lambda_t}$). However, this model faces endogeneity stemming from simultaneous causality. Fluctuations in strait traffic may drive changes in exports; on the other hand, changes in exports may be driving fluctuations in strait traffic. This issue causes the residual (ϵ_{ijkt}) to be correlated with the regressor (T_{it}), leading to biased coefficients.

To address this endogeneity, we use a two-staged least squares (2SLS) method whereby a random shock is exploited to tease out the exogenous effect of our predictor

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[7] We bold terms for matrices comprised of vectors of indicator variables, representing fixed effects

of interest. In the following section, we explain our 2SLS methodology and their associated assumptions.

2.3.1 First stage of the 2SLS

The first stage of the 2SLS estimates any effect piracy attacks in and about the SOH have had on subsequent vessel traffic through the Strait and is based on the gravity model of trade, which is used extensively in the existing literature to model trade flows (Anderson and Van Wincoop, 2003; Helpman et al., 2008). It is given by the following equation.

$$T_{it} = \alpha_1 + \beta_1 Z_{i,t-1} + \beta_2 Z_{i,t-2} + \beta_{3,i}\boldsymbol{\Gamma_i} + \beta_{4,i}\left(Z_{i,t-1}\right)(\boldsymbol{\Gamma_i}) + \beta_{5,i}\left(Z_{i,t-2}\right)(\boldsymbol{\Gamma_i}) + \beta_{6,t}\boldsymbol{\Lambda_t} + \epsilon_{it}$$

[Equation 2.2]

In this equation, T_{it} is the number of vessels that visited country i that also passed through the SOH in year t. These values are obtained through the vessel-linking algorithm explained in Section 2.2.3, which links a vessel to a country if that vessel visited the country within a one year window of transiting the SOH. $Z_{i,t-1}$ and $Z_{i,t-2}$ are lagged piracy attacks within the Strait involving vessels linked to country i. The first stage sample includes all countries with vessels transiting the SOH; therefore, i can be either a PGC nation or an importing nation. Note that the first stage is conducted at the country level and not bilaterally.[8]

Lagging of the attacks is done to mitigate endogeneity and is based on the work of Bensassi and Martinez-Zarzoso (2012), who argue that while piracy in a region two years ago can affect shipping through that region now, current shipping levels had no effect on piracy in the region two years ago (Bensassi and Martínez-Zarzoso, 2012; Martínez-Zarzoso and Bensassi, 2013b). These authors also suggest that piracy attacks lagged only one year may have confounded impacts from autocorrelative trends in shipping trade, but we include the lag-1 term along with the lag-2 in order to account for any possible decay in piracy effects on the ship traffic. We also include fixed effects for country, $\mathbf{\Gamma}_i$, and year, Λ_t, as well as interactions between country fixed effects and piracy attacks for both the lag-1 and lag-2 terms to capture heterogeneity in the effect of attacks among the countries. While the data indicates that attacks are randomly assigned by country, the effects of these attacks can differ based on underlying country characteristics. Finally, the residual ϵ_{it} accounts for the variation of traffic not explicitly attributable to the defined variables.[9]

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[8] The first stage aims to tease out the causal effect of *overall* piracy events on vessel traffic of a country, and not just the effects of an event occurring en route from a PGC country to an importer. We therefore do not specify the first stage bilaterally.

[9] Vectors of fixed effects are in bold; these will have different coefficients for each factor level.

2.3.2 Second stage of the 2SLS

The solution of Equation 2.2 yields the coefficients β_1 through $\beta_{6,t}$, which in turn are plugged back into the equation along with all the independent variables (i.e., those on the RHS) to solve for $\hat{T}_{it}$, which are estimates of Strait transit accounting for any piracy-induced reductions in traffic to/from nation i in year t in each Strait. These predictions are then input to the second stage of the 2SLS (Equation 2.3) which relates the estimated shipping impacts to annual PGC trade in fuels with every other country in the world, in terms of monetary values (2016 $).

$$Y_{ijkt} = \alpha_2 + \lambda_1 \hat{T}_{it} + \lambda_{2,j} \boldsymbol{\Phi_j} + \lambda_{3,t} \boldsymbol{\Lambda_t} + \mu_{ijkt}$$

[Equation 2.3]

In this equation, Y_{ijkt} is exports of product k from PGC i to country j in year t. As in Equation 2.1, Equation 2.2 also includes country-level fixed effects ($\boldsymbol{\Phi_j}$; note that in this instance for country j), year-level fixed effects ($\boldsymbol{\Lambda_t}$) and the residual variable μ_{ijkt}. Given that Equation 2.3 relies on the estimates $\hat{T}_{it}$ rather than T_{it}, we adjust the standard errors in the second stage of the 2SLS to account for the propagation of uncertainty associated with multi-level regressions. Details on this adjustment are provided in Section S3 of the Supplementary Material.

For our analysis, the most important output of Equation 2.3 is the regression coefficient λ_1 after it has been multiplied by -1. This is because $-\lambda_1$ represents the estimated influence a one vessel *decrease* in chokepoint shipping traffic has on average fuel exports between each PGC and each of its importers. Equation 2.3 is run iteratively to arrive at separate regressions for individual PGC and commodity pairs.

2.4 Results

2.4.1 First stage: the effect of piracy on vessel transit

An estimation of Equation 2.2 yields country-level estimates of the effect that an additional piracy attack has on shipping traffic through the SOH two years after the attack. Detailed results from the regression are given in Section S7 of the Supplementary Material. Here we highlight a generalization of these findings using the regression results from the following simplified version of **Error! Reference source not found.**, in which country-level characteristics are still controlled for but interaction terms have been omitted. By omitting interaction terms, we are effectively showing the *average* effect of piracy incidents on vessel transit rather than the country-specific effects of these incidents, which can vary based on heterogeneities among countries' responses to risk.

$$T_{it} = \alpha_3 + \pi_1 Z_{i,t-1} + \pi_2 Z_{i,t-2} + \pi_{3,i}\boldsymbol{\Gamma_i} + \pi_{6,t}\boldsymbol{\Lambda_t} + \varepsilon_{it}$$

[Equation 2.4]

where π_{1-3} and π_6 are the equivalents of coefficients β_{1-3} and β_6 in Equation 2.2. Equation 2.4 yields an estimate of the average impact of a single attack on shipping two years out (π_2).

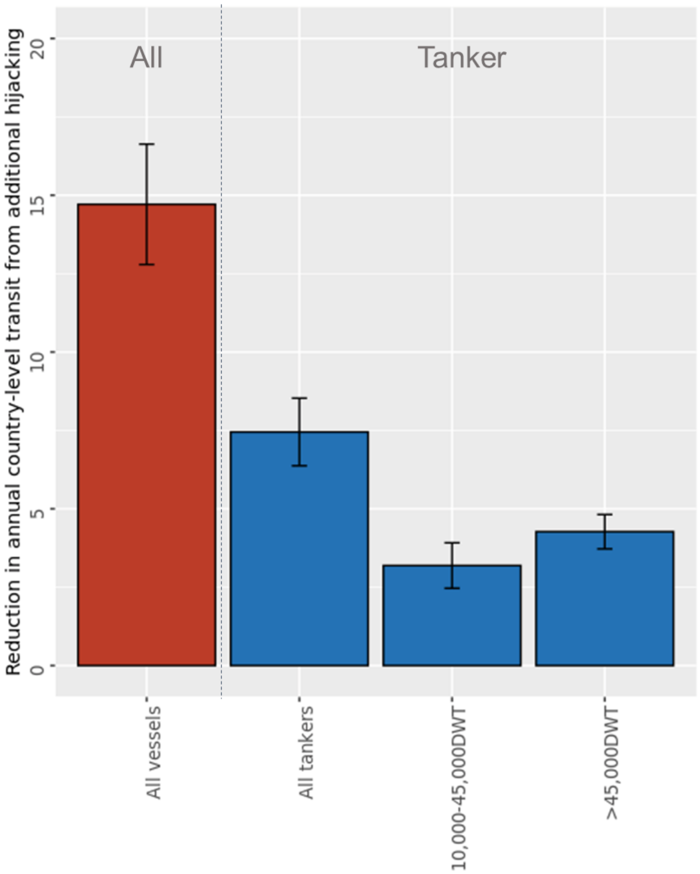

Figure 5. The effect of an additional piracy attack to vessel transit two years later. Each bar represents the coefficient ($\boldsymbol{\beta_2}$) on our primary predictor of interest ($\boldsymbol{Z_{i,t-2}}$), estimated using Equation 2.2. Separate regressions are run to estimate different coefficients by the type and capacity of vessels. Vessels other than tankers also transit the strait; the effects of an attack on these vessels are confounded in "All vessels" (red bar). Error bars represent the 95% confidence interval on each coefficient. We do not have small tankers (1-10,000DWT) in our sample; we therefore omit this group from this figure.

Results suggest that for each country i, an additional attack in the SOH is associated with a 14.71 vessel-reduction in overall traffic through the Strait. In addition, each piracy incident affects subsequent movement by tankers, which are vessels relied upon by PGC for fuel exports. Tanker transits fall by an average of 7.5 vessels per country for each additional attack. Furthermore, the relationship between a piracy event and tanker traffic grows with vessel capacity. This suggests that owners of larger vessels, particularly those carrying higher-value commodities, such as fuels, become more risk averse to potential attacks years after one has occurred. Tables with these results are included in Section S8 in the Supplementary Material.

2.4.2 Second stage: the effect of vessel transit on trade

The second stage of the 2SLS yields λ_1, the coefficient that after being multiplied by -1 represents the average impact of a one-vessel reduction in large tanker traffic on a PGC's energy exports by destination and year. We run this regression for each PGC and all the countries it trades with for every fuel product that the PGC exports (e.g., crude oil, LNG, diesel). The result of each of these regressions is $-\lambda_{1_k}$, a $-\lambda_1$ associated with every product k for each individual PGC. Results for country-by-country, fuel-by-fuel iterations are shown in Section S11 of the Supplementary Material. Note that the program is coded so that only samples with greater than 50 observations will run.

We further express trade impacts for each PGC as total annual impact per product, A_k, given by:

$$A_k = (-\lambda_{1_k})(N_k)$$

[Equation 2.5]

Here, $-\lambda_{1_k}$ is the average impact per destination country per product k, and N_k is the mean number of PGC export destinations per year for fuel type k over all years of the analysis.

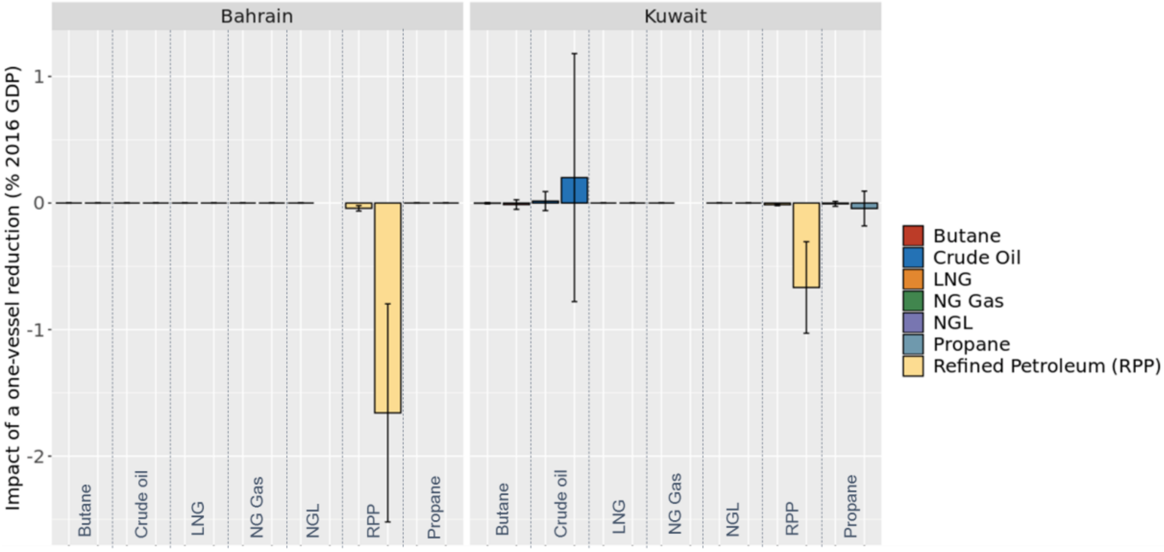

Figure 6. Impact of a one-vessel reduction on fuel exports moving through the SOH. Values are represented as % of 2016-level GDP. Second stage regressions are run iteratively by PGC and product. Each of these products is represented by a different color and bar. The bar on the left (a) represents the average effect on fuel exports moving to each importer ($\boldsymbol{j}$), divided by 2016-level GDP. The bar on the right (b) represents the potential total reduction in exports ($\boldsymbol{A_k}$) divided by 2016-level GDP. Only results for Bahrain and Kuwait are presented. Results for other PGC were not statistically significant and can be found in the Section S11 of the Supplementary Material.

Results suggest that soft restrictions through the SOH would only have significant economic impacts on select PGC. Bahrain, for example, could stand to lose, on average, 0.04% of its 2016 GDP if carriers reduced shipments by just one vessel's worth of RPP exports to just one its importers (i.e., $-\lambda_{1_{petroleum}}$). And if the single ship reduction in the exports were extended across all of Bahrain's trading partners ($A_{petroleum}$), the country's loss could reach 1.6% of its 2016 GDP. For Kuwait, we estimate the range in potential losses to be between 0.01% and 0.67% of 2016 GDP based on reductions in RPP exports. Crude oil seems to indicate a positive effect, but is not statistically significant. The confidence intervals for other PGC span zero, suggesting that there is no significant effect (both ordinally and in terms of magnitude). Figure 6 is a graph of A_k (left bar) and $-\lambda_{1_k}$ (right bar), in terms of percentage of each PGC's 2016 GDP, for every fuel product exported by the PGC.[10] Note that we present the results of this analysis, regardless of statistical significance, to increase the transparency of these results. Section S10 in the Supplementary Material presents the results in table form by country, across fuels.

The results shown in Figure 6 represent the combination of both the direct and indirect effects of transit restrictions on energy exports from the Persian Gulf region. The direct effects are those attributed to the value of the actual cargo carried on the vessels, whereas the indirect effect includes the intermediate to long-term response by PGC when faced with increased risk to shipping.

2.5 Discussion

2.5.1 Limitations of this study

While information on ship positions is available at hourly time scales, and piracy events are published as or shortly after they happen, the only complete, harmonized,

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[10] It is important to note here that an analysis of value faces additional challenges stemming from confounded covariates, largely through oil prices (e.g. higher oil prices would hide the fact that lower volumes of oil are traded).

publicly available datasets on international trade down to the commodity level across multiple years for all countries are the annual data published by the UN COMTRADE Program and CEPII, whose BACI dataset we use here. Consequently, our study does not capture intra-annual fluctuations in attacks, vessel traffic, and international trade. As noted previously, however, variations in ship traffic through the Straits on time scales shorter than 1-2 years may be endogenous, a problem that would prohibit us from being able to statistically discern subsequent changes in shipping frequency following piracy events. Thus, for our purposes, the annual resolution of the data we use is sufficient.

A more significant issue is that the vessel traffic data that we use do not contain information on what cargo each vessel is carrying, so we are not able to differentiate between tankers carrying fuels vs. chemicals or potable liquids. Instead, we rely not only on the categorization of each vessel (e.g. tanker, bulk carrier, research, passenger), but also its capacity (in deadweight ton) to run separate regressions in the first stage of the 2SLS. This means that we are effectively estimating the effect of traffic reductions for all large tankers and attributing them to fuel exports. This is not an unreasonable assumption given that the vast majority of PGC exports consist of fuels carried on tankers. Nonetheless, our results may underestimate the lagged impact of piracy events on PGC trade in these commodities.

Another critical element to our analysis is the vessel-matching algorithm used to count the number of ships each country sends through each Strait. This algorithm attempts to overcome our lack of information on each vessel's route by approximating the route as segments between each port visited by the vessel. We allow for this approximation because the final destination of the vessel and thus its cargo may be well beyond the first ports it stops at directly after transiting a Strait. For instance, a tanker starting in Qatar may dock at India before making stops in Singapore and Japan. Our algorithm links this vessel to all of these countries, not just Qatar and India, so Qatar would be identified as shipping fuels to India, Singapore and Japan. The end result may be an over inflation of the number of vessels transiting the Strait that we associate with each country. This error would impact our first-stage regression, which uses country-level vessel transit data as the dependent variable. In our second-stage regression, N_k in Equation 2.5 will not be impacted, as this value is based on bilateral trade data and the actual number of trade partners per PGC per commodity, not on modeled ship routes.

2.5.2 Possible drivers of differences in PGC energy export sensitivity

2.5.2.1 Geography and other events affecting exports from 2010-2016

The second stage of the 2SLS suggests that the effect of piracy on PGC energy exports differs by energy exporter and fuel type. With respect to energy exporter, our results indicate that piracy does not have a substantial effect on fuel exports from Oman, Saudi Arabia, Iran and Iraq. One possible reason for the results for Oman and Saudi Arabia is that neither country's fuel exports are limited to being shipped exclusively through the SOH. Oman for instance has direct access to the Indian Ocean, while Saudi Arabia can avoid the SOH by moving crude oil from its eastern oil fields through its East-West pipeline (capacity of 5 Mbbl/day) - to the country's western ports along the Red Sea.

Iran is another country with ports outside the Persian Gulf, but its export capacity at these ports is quite limited. Iran's port in Chabahar along the Arabian Sea remains largely isolated from the rest of the country, and while it has a port in Neka along the Caspian Sea, Iran's major oil and gas ports (Kharg, Lavan and Sirri Islands) are all in the Persian Gulf (U.S. Energy Information Administration, 2019b). The key driver for Iran's resilience to a soft restriction may be due to the fact that for much of the period of our analysis, the country's exports were already restricted by U.S. and EU oil sanctions which limited Iran's crude oil exports to 1.1Mbbl/day (50% of 2011 levels) (Laub, 2015). These restrictions were not lifted until 2015, a year before the end of our analysis. (European Council, 2015). Similarly, the timeframe of our analysis also extends across the Iraq War (which started in 2003). As with the sanction restrictions on Iran's exports, this war-induced reduction in Iraq's exports may also be a reason for why the country's exports do not show a sensitivity piracy events in our analysis.

2.5.2.2 The viability of pipeline as an alternative to shipping

It is tempting to infer that PGC energy exporters that appear to be resilient to piracy in our analysis are less at risk because they have the capacity to export fuels outside the region via pipeline. We find no significant evidence of this, however, when we subset the analysis to compare PGC trade with pipeline-sharing countries to PGC trade with countries that require SOH access.[11] To do this, we ran the following specification:

$$Y_{ikt(p=1)} = \alpha_5 + \zeta_1 Y_{ikt(\,p=0)} + \zeta_2 \Gamma_i + \zeta_{3,t}\gamma_t + \zeta_{4,k}h_k + e_{ikt}$$

[Equation 2.6]

Here $Y_{ikt(p=1)}$ represents exports of fuel k for PGC i in year t that is destined for a pipeline-sharing country, while $Y_{ikt(p=0)}$ represents exports destined for a country that requires chokepoint transit. Γ_i are fixed effects for PGC, γ_t are fixed effects for year, and h_k are fixed effects for product.

Results showed that a 1-ton increase in fuel exports to SOH-dependent destinations causes a 0.01-ton increase in exports to pipeline-sharing countries.[12] This

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[11] We define pipeline-sharing as sharing an active or idle pipeline. These data are compiled using historical maps from Kandiyoti (2008) and the Harvard WorldMap (Guan et al., 2012; Kandiyoti, 2008). A table illustrating pipeline relations can be found in Supplementary Material (S13)

[12] A full table of results can be found in S14 of the Supplementary Material.

suggests that any significant impact in the second stage analysis is driven by trade with SOH-dependent importers rather than pipeline-sharing land importers. In other words, switching from ship to pipeline transport does not appear to be a viable alternative for the PGC to compensate for reductions in maritime trade. And given that pipelines carry fuels to fixed destinations, most of the PGC may continue to opt for the flexibility offered by shipping and thus move their fuel exports through the SOH even when faced with increased risk. This is particularly the case for crude oil exports, which not only provide PGC with a large share of their revenue but also can only be produced in and shipped from this region. Crude oil exports are effectively resilient to soft restrictions in the SOH because of their geographic specification, rather than each PGC's relative sensitivity to risk.

2.5.2.3 Differences between the crude oil and refined petroleum product markets

The PGC exporters that we find to be sensitive to piracy events are Bahrain and Kuwait. Furthermore, rather than crude oil, it is these countries exports of RPP that appear to decline two years after a piracy event. Unlike several of the other PGC, both Bahrain and Kuwait are essentially limited to shipping exports through the SOH, particularly because these exports are primarily sent to East Asia, with South Korea and Japan being the biggest importers of the RPP. The absolute values of energy exports from these countries are relatively small for the region. In 2017, energy exports totaled to

$2.44B for Bahrain and $39.1B for Kuwait, compared to $130B for Saudi Arabia and $71.7B for the UAE (Simoes and Hidalgo, 2011). However, the energy exports still make up more than half of each nation's total exports and are a major fraction of their GDP. Therefore, even a minor disruption to international shipping, which would have a marginal impact on the large amount of exports from the other PGC, would significantly affect Bahrain and Kuwait's exports. This includes the RPP component of these exports, which on average equate to 28.3% of Bahrain's total annual exports (10.4% of its GDP) and 19.3% of Kuwait's total annual exports (11.9% of its GDP).

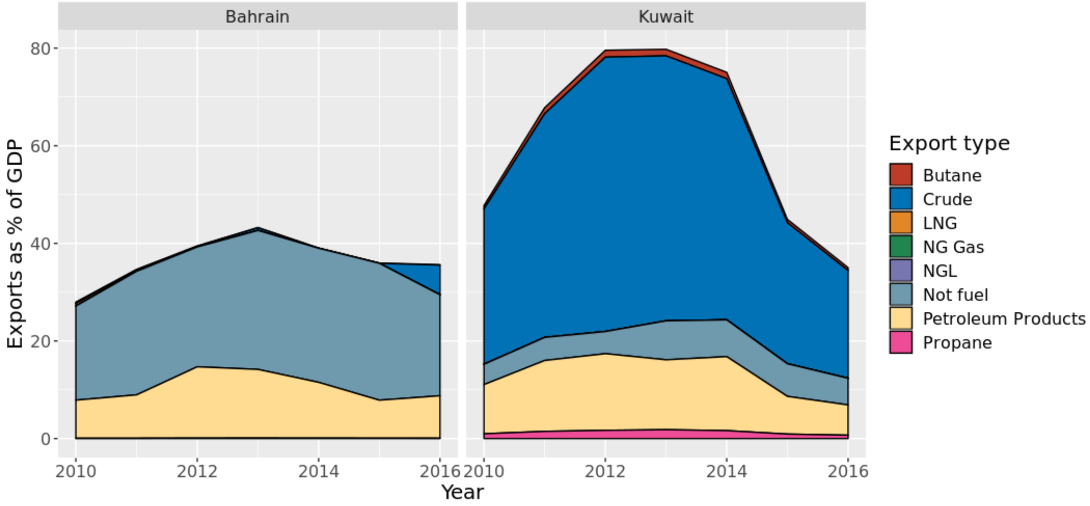

Figure 7. Exports as % of GDP, differentiated by fuel type and non-fuel commodities. Based on author calculations using the BACI bilateral trade database. Non-fuel exports include all other commodities exported by the given PGC. GDP and export values are adjusted for inflation.

Note in Figure 7 that RPP make up roughly 90% of Bahrain's energy exports each year. The country also exports a large amount of non-energy products (e.g. iron ore) so overall the RPP exports do not make up a large share of Bahrain's GDP. In contrast, the majority of Kuwait's energy exports are in crude oil (66.6% of its total exports, on average, per year). While the RPP exports make up a smaller share of Kuwait's overall energy exports, the latter represents nearly 90% of the country's exports, making the RPP exports a much larger share of Kuwait's GDP each year.

This then leads to the question of why Kuwait's RPP exports are sensitive to piracy while its crude oil exports, like those of the other PGC, are not. We hypothesize that this is because of differences between the crude oil market and the RPP market. The global crude oil market is an oligopolistic market in which the sellers of crude oil, and the PGC exporters in particular, have significant influence on the global supply of crude oil. On the other hand, the RPP market is a competitive market where importers have many more choices for where they can acquire RPP, and any set of exporters have much less influence on the global supply of RPP. Consequently, while a soft restriction may significantly increase the price of crude oil, many importers of crude oil will still buy the critical commodity because they have few other options for sellers. However, if a soft restriction increases the price of RPP coming from an exporting region, importers can turn to other exporters and/or start taking steps to increase their domestic production of RPP. In either case, those RPP exporters affected by a soft restriction risk losing market share that may not be recovered even years afterward. We argue that this in fact may be an important reason our analysis indicates a decline in Bahrain's and Kuwait's RPP exports years after a piracy event. Furthermore, we argue that the greater relative impact that soft restrictions can have on smaller energy exporters also helps explain why these countries' RPP exports exhibit a statistically significant decline years after a piracy event while the RPP exports from larger PGC do not. We suggest that the latter's RPP exports are not as sensitive to a soft restriction because their primary export is crude oil.

2.6 Conclusions and Policy Implications

Our study finds that there is little significant long-term effect of soft restrictions in the form of piracy on energy exports from most of the PGC. The exception to this is RPP exports from Bahrain and Kuwait, the smallest energy exporters among the PGC. These countries export significantly less energy than their counterparts in terms of absolute magnitude, but their exports make up a large share of their GDP. A marginal effect of a soft restriction to energy shipping will therefore be more significant to these countries than larger energy exporters like Saudi Arabia. These findings have two key takeaways for policymakers:

First, importer energy security may be at odds with exporter energy security and thus at odds with the resilience of energy exporters to shipping disruptions. Our study found that RPP exports, because they operate in a competitive market, are more sensitive to soft restrictions through the SOH. This may be driven by the fungibility of RPP; the buyer in this market can switch to another RPP exporter because RPP can, and is, produced in many non-PGC regions. Simply put, when the energy importer has more options of where to buy from, the energy exporter becomes more sensitive to trade disruptions.

Second, in the case of energy exports from the PGC, the story has been and will continue to be about crude oil. Our study found that crude oil exports are resilient to soft restrictions because they operate in an oligopolistic global market, can only be produced in select geographies, and are critical to meeting global energy demand. The global demand for crude oil is so great, in fact, that importers are willing to send their military to the Persian Gulf help protect the flow of crude exports. India, for instance, in 2008 signed a defense cooperation agreement with Qatar to protect maritime shipping (Ulrichsen, 2009), and China recently increased its naval presence in the SOH to protect its crude oil exports from the region (Cornwell, 2019). The flow of crude oil through the SOH is well-protected because it is a product that is needed by virtually all regions but which can only be produced in a select few.

This raises questions on what would happen as global energy demand shifts away from crude oil. Recent projections from the International Energy Agency indicate that primary energy supply from crude oil will drop by nearly 50% between 2016-2040 (International Energy Agency, 2017a). This supply is projected to be met by either natural gas or low-carbon fuels (i.e. hydro, wind, solar). Will international investment in securing the SOH drop with the drop in global demand for crude oil? Will this exacerbate the vulnerability of RPP exports from the region to soft restrictions in the Strait? These are questions that policymakers need to consider to facilitate energy security in the future.

3 Hybrid Input-Output Analysis of Embodied Energy Security

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3.1 Introduction

Energy security entails the uninterrupted availability of energy at an affordable price, and is often considered with respect to nations' dependence on net imports of energy resources, refined fuels, and electricity (Energy Charter Secretariat, 2015; OECD, 2008; "Valuation of Energy Security in the United States," 2017). Nations, however, not only consume energy directly, but also indirectly in the form of energy incorporated in goods and services during their production. Energy security therefore not only relies on the global flow of primary and secondary energies, but also on the trade of goods and services produced using energy. In fact, trade strategies for critical goods and services can also be viewed in the context of energy security; whichever of these is not produced domestically must be produced in other countries using the latter's energy resources. Consequently, by shifting production overseas, a nation not only saves on energy used domestically, but also increases its dependence on foreign energy.

How much this dependence truly affects energy security remains to be determined. Such an evaluation first requires a clear distinction between several important types of energy. A nation's economic output, and thus its citizens' standard of living, depends on the nation's use of *primary* energy, such as natural gas, and *secondary* energy, such as electricity (Lambert et al., 2014). In turn, this consumed energy is generally referred to as *embodied* energy and consists of two components, direct and indirect energy. *Direct* energy is the primary energy that an economic sector consumes in producing a good or service. Examples include coal used to smelt iron, natural gas used to make fertilizer, and enriched uranium to generate electricity. In contrast, *indirect* energy (also referred to as *embedded* energy in this paper) includes the energy in steel embedded in the iron used to forge the steel, the energy embedded in the fertilizer used to grow the crops, and the energy in a cell phone embedded in the electricity used to assemble the phone. Note that many goods and services involve multiple forms of indirect energy. In the case of the mobile phone, for example, its assembly also includes indirect energies from crude oil refined into the phone's plastic components, and from natural gas burned in a furnace to make the phone's glass components. Furthermore, in the current era of global supply chains, some of these components will have been produced domestically, while others will have been imported from overseas. Thus, the indirect energy requirements of a nation's economic sectors are much larger, and have a much wider geographic scope, than their direct energy requirements.

There are at least three ways that a nation's reliance on indirect energy imports could influence its energy security. The first is in terms of economic security. For example, say a nation imposes a sanction on primary energy imports from a major energy exporter. While the objective of the former would be to impact the latter's direct energy exports, the sanctioning nation could still end up supporting the sanctioned nation if the latter's primary exports were used by another country to make a non-energy good that the sanctioning nation imports. Secondly, the security of indirect energy imports is relevant to supply chain security. An international supply chain for a critical service, such as telecommunications, may seem secure because the equipment's components are made and/or operated by sectors in different countries that are politically stable and have good relations with one another. The indirect energy in these components, however, may ultimately be sourced by yet another country that is politically unstable or a geopolitical adversary (Kruyt et al., 2009). And third, indirect energy security bears on environmental security. Say a nation seeks to reduce its greenhouse gas emissions by shifting to greater reliance on domestically-sourced renewable energy. This effort is undermined if the nation continues to import goods and services rich in indirect energy produced using fossil fuels (i.e. "carbon leakage") (Babiker, 2005; Chen and Wu, 2017b). For all three types of security issues, the global market via international trade gives opportunities to reduce the risks stemming from a nation's indirect energy imports. A nation cannot identify and preemptively act on these options, however, without first knowing where the risks associated with its indirect energy imports actually lie.

A spate of recent papers has evaluated embodied energy in the context of international trade, of which a few address energy security (Chen et al., 2018, 2019; Tang et al., 2013). Of particular note is a series of papers led by G.Q. Chen and X.F. Wu that attempt to trace embodied energy flows through international trade from their sources to their sinks (Chen and Wu, 2017b; Wu et al., 2019; Wu and Chen, 2017). Chen et al. (2018) used the framework adopted by these authors and then employed network analysis metrics to evaluate energy security (Chen et al., 2018). In these papers, *embodied energy* is estimated as the sum of direct and indirect energy inputs. In our study, we build on the existing literature by separating out and comparing direct and indirect energy flows, rather than combining them. Furthermore, in the recent papers just cited, energy flows are traced from the point at which direct energy is first consumed, and energy security is measured based on where a country sources its energy-intensive goods and services. Left unaddressed is how the energy security of the countries producing those energy-intensive goods and services may impact the energy security of consumers further downstream in the supply chain. When a country consumes a product that is manufactured abroad, the production's energy requirements are generally excluded from its energy security measurements. In this study, we add this crucial component by linking the energy security of energy-consuming countries back to the energy security of countries that first produced, rather than exploited, the energy, thus expanding the boundaries of the global energy system.

Empirical methods grounded in economics and developed in industrial ecology have become important tools for estimating embodied energy and their associated emissions. Input-output models (IO) assess each sector's direct and embodied requirements by arranging the major sectors of an economy along both the rows and columns of a matrix. While originally developed to examine the financial value of the goods and services flowing among sectors, IO has since also been modified to estimate sector-level energy consumption to better target energy efficiency policies and trace energy-related emissions. This approach is commonly called an environmentally extended IO analysis (EEIO). Studies have used EEIO to estimate the size and drivers of energy consumption in specific industries, such as construction (Guo et al., 2019; Hong et al., 2016), manufacturing (Sun et al., 2018), and agriculture (Cao et al., 2010), as well as entire national economies (Feng et al., 2015; Lenzen and Murray, 2001; Machado et al., 2001).

More recently, IO has been extended to include large-scale multi-regional input-output models (MRIO) that trace financial and material flows in international trade. Three databases that have been widely used for this purpose are the World Input-Output Database (WIOD), EXIOBASE, and the Eora Global Supply Chain database (Lenzen et al., 2012a, 2013; Stadler et al., 2018; Timmer et al., 2015). These databases rely on a direct input-output framework (DIO), in which researchers first calculate financial flows within an economic system and assign energy requirements *ex-post* using environmental extensions (Lindner and Guan, 2014a). Energy requirements are therefore directly linked to financial requirements. Studies that build on these models, or the MRIO framework in general, have found that major economies import a large percentage of embodied energy from developing countries with energy-intensive industries (Chen et al., 2018; Chen and Wu, 2017b). This also means that the former are importers of energy-related emissions of the latter. For example, the United States is a net importer of carbon emissions associated with trade, while China is a net exporter (Davis and Caldeira, 2010).

An important limitation of DIO, in the context of global MRIO, is that it often aggregates energy flows such that the origins of this energy are not defined. Thus, while DIO is able to trace energy consumption through an economy starting from the points at which it first uses energy, it does not follow the energy value chain to the ultimate sources where the energy resources were first extracted (Tang et al., 2013). This can be done, however, using an extension of IO known as hybrid-unit input-output (HIO) analysis which, like DIO, is based on the global MRIO framework. In HIO, rows and columns representing energy sources are inserted into the underlying IO matrix such that energy production and consumption are included as additional *physical* flows in the economic system. HIO is also commonly referred to as a mixed-unit IO analysis because its underlying IO table includes energy-to-monetary units and monetary-to-energy units (e.g. J/USD and USD/J). This is in contrast to DIO, which includes monetary transactions in the underlying IO table and a separate table of environmental extensions.[1] A significant advantage of this is that HIO eliminates the assumption required by DIO that one dollar of output to one sector is equivalent to a dollar of output to another (Kitzes, 2013). DIO uses this assumption to estimate energy flows from financial flows. However, sectoral differences in energy prices make clear that the proportionality assumption does not hold in reality. For example, electricity prices paid by industrial sectors are often lower than those paid by commercial sectors, which in turn are even lower than the prices charged to the residential sector (U.S. Energy Information Administration, 2015). Furthermore, HIO explicitly maps feedbacks between energy sectors and non-energy sectors. For instance, coal mining requires substantial amounts of electricity. Some of that electricity is generated in nuclear power plants fueled by uranium. Therefore, there is some uranium-based primary energy that is required in the production of coal-based primary energy. HIO would capture this energy flow, while DIO would not.

HIO was introduced in a seminal paper by Bullard and Herendeen (1975) (Bullard and Herendeen, 1975), in which the authors apply a hybridized approach to the 1967 input-output table for the United States. Since it was introduced over 50 years ago, HIO has been used mainly to assess energy use by single economies or sectors. Treloar

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[1] DIO analyses are often referred to as hybrid IO because they combine a process-based life cycle approach to an input-output approach. We there note that in this study, we define HIO as a hybrid-*unit* model.

(1997) uses HIO to estimate the energy that is embodied in the Australian residential sector (Treloar, 1997). Liang et al. (2010) builds an HIO table that traces both energy and pollutants in Suzhou, China (Liang et al., 2010). Lindner and Guan (2014) compiles a national-level HIO matrix to estimate total per capita energy consumption in China (Lindner and Guan, 2014b). At a more regional level, Merciai and Schmidt (2018) builds on EXIOBASE to compile an HIO for 47 countries and the rest of the world (Merciai and Schmidt, 2018). Methodological advancements have also been made since Bullard and Herendeen (1975), with some combining HIO with other modeling techniques. Examples include Kagawa and Inamura (2001) which applies a structural decomposition analysis to an HIO for Japan (Kagawa and Inamura, 2001), and Igos et al. (2015) which combines a computable general equilibrium model with HIO for Luxembourg (Igos et al., 2015). Other methodological advancements have focused more on the mechanics and validation of the HIO framework (Crawford, 2008; Guevara and Domingos, 2017; Minx et al., 2009). Yet few studies have applied HIO to a global MRIO framework, primarily because HIO is very data intensive (Kitzes, 2013; Miller and Blair, 2009).

While HIO is data intensive, it allows us to understand global energy security as a metric comprised of two links: (i) the link from primary energy exporters to primary energy imports (which is the link cited for most energy security studies) and (ii) the link from exporters of energy-intensive products to their importers. By combining the two links, HIO can trace energy from the primary energy exporter to the final energy sink (i.e. the importer of energy-intensive products). Whereas DIO addresses (ii), its relationship to (i) can only be evaluated using the HIO. We address this research gap by taking advantage of the Eora Global Supply Chain database and a growing library of other large international databases (Lenzen et al., 2012a) to develop a single global energy database that traces the physical flows of 13 energy resources and the monetary flows of 26 non-energy sectors within and between 136 countries over 16 years (2000-2015). The result is what we call the Hybridized Option for Modeling Input-output Energy Systems (HOMIES). HOMIES advances our understanding of embodied energy in the global economy by: (1) explicitly (and thus endogenously) modeling the production of specific energy resources (e.g. coal, crude oil, petroleum); (2) representing energy flows from the point of production, rather than the point of consumption; (3) modeling energy inputs bidirectionally, allowing the user to trace the embodied energy used to extract and generate energy resources; and (4) representing primary-to-secondary energy conversion by disaggregating energy flows.

The indirect energy requirements resolved by HOMIES also effectively elucidate the indirect energy security of the global economy. In this study, we assess the indirect energy dependence of global trade and the major trading nations. The former is measured using import dependence, or the fraction of imports over total consumption, while the latter is assessed based on the indirect energy import and export portfolios of the world's largest energy trading nations. Our objective is to identify economic areas, both geographic and sectoral, in which indirect energy security contrasts sharply with direct energy security. These discrepancies have significant implications for nations' energy security. They identify areas that may be more vulnerable to energy shocks than they appear to be based on international flows of direct energy. The origins of indirect energy imports may lie outside of a nation's direct energy trade network. The nation may thus be dependent on a primary energy exporter without having the policy leverage to ensure sustained, affordable energy exports. Because of the highly spliced nature of some supply chains, nations may not be aware that indirect energy linkages even exist. This presents a crucial knowledge gap that has the potential to undermine national energy security.

We begin this paper by comparing existing IO methodologies to HOMIES. We then identify and quantify the primary energy resources that sourced the world's direct and indirect energy requirements from 2000-2015, breaking these requirements down further into the fractions that were either produced domestically or imported from abroad. From there, we examine the direct vs. indirect energy intensity of each major sector in the global economy, and conclude by quantifying the import dependence and portfolio diversity of ten major nation's indirect vs. direct energy requirements.

3.2 *Methods and Data*

3.2.1 Input-Output Analysis (IO)

IO analysis hinges on the following identity:

$$x = Z + f$$

[Equation 3.1]

Where x is a vector of total output in an economic system, Z is a matrix of intermediate industry transactions among economic sectors (agriculture, mining, etc.), and f is a vector for final demand. Using Equation 3.1, a "direct requirements" matrix, A, is solved:

$$\mathrm{A} = \left[\alpha_{i \to j}\right] = \mathrm{Z}\hat{x}^{-1}$$

[Equation 3.2]

In which $\hat{x}^{-1}$ is the diagonalized inverse (a matrix) of x, and the matrix A consists of the direct input from every sector i in an economy that goes into producing one unit of output from each sector j in the economy (Figure 8a). Finally, a "total requirements" matrix L is arrived at by subtracting A from its corresponding identity matrix and inverting the difference:

$$L = (I - A)^{-1}$$

[Equation 3.3]

This last equation is the Leontief identity, named after the economist who pioneered the use of Equations 3.1-3.3 to examine the inputs and outputs of an economy. The total economic output therefore equals $x = Lf$.

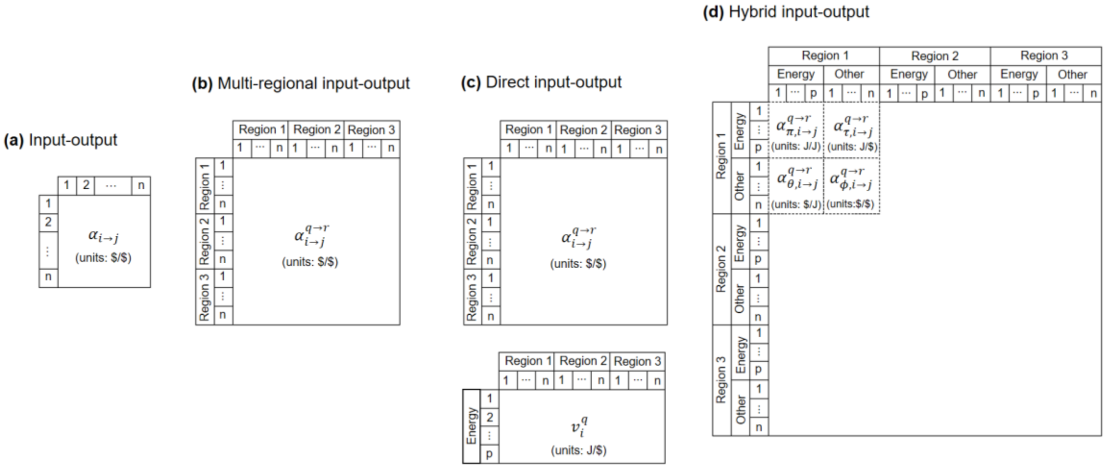

Figure 8. Schematic of direct requirements matrices, by input-output model framework. Figures represent: (a) the case of a single-economy single-unit IO model, (b) the case of a single-unit MRIO model, (c) the direct IO model, and (d) the hybrid-unit IO model.

The scope of analysis is extended to the global economy in MRIO by expanding the direct requirements matrix to include u regions and n (non-energy) sectors (Figure 8b). The new direct requirements matrix represents the per-unit direct requirements by sector j in region r of output from sector i in region q.

3.2.2 Direct Input-Output Analysis (DIO)

DIO, used widely in existing literature, is effectively a two-step estimation approach, in which L is estimated as described in Section 3.2.1 and then multiplied by another matrix, V, containing direct energy requirements (i.e. energy intensity) by each economic sector (Figure 8c) (Chen and Wu, 2017b). Data on these energy inputs are in physical units and are published by organizations like the International Energy Agency (International Energy Agency, 2018b). DIO can be applied to a single nation or the global economy to analyze the sum of direct and indirect energy involved in sectoral transactions. As noted previously, others have referred to this sum as embodied energy, a convention that we will also follow here.

DIO includes the consumption of p energy resources by each of the n sectors in u regions, so $\mathrm{E} = [e_i^r]$ and represents the region-specific direct energy inputs into each sector.[2] Note then that E has p rows and nu columns. The per-unit energy input for each sector (i.e. the direct energy intensity), V, is obtained by dividing the total output of these sectors into E:

$$\mathrm{V} = [v_i^r] = \mathrm{E}\hat{x}^{-1}$$

[Equation 3.4]

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[2] Here, u represents the total of the r (or q) regions represented in HOMIES. p and n are the total energy resources and non-energy sectors represented, respectively. i can represent either an energy resource or non-energy sector.

Finally, multiplying V by L (from Equation 3.3) yields the total energy intensity of an economic system, which permits tracking of indirect energy flows from the point of initial consumption. What cannot be tracked in DIO, in the context of global MRIO, is indirect flows of energy from their points of production (Tang et al., 2013).[3] This is because in DIO the input flow of energy resources is aggregated such that the originating region of these energy resources is lost. For instance, crude oil imported by China from Saudi Arabia is combined with the former's crude oil imports from Indonesia. So, while DIO will capture how crude oil consumed by China ripples through the global economy, the analysis will not reveal whether, where, and how much Saudi Arabian crude is embodied in a region's final consumption of Chinese exports.

DIO also suffers limitations in tracking direct energy flows when multiple forms of energy production are lumped together into the same sector. For instance, the "Mining and Quarrying" sector in Eora MRIO tables includes the production of coal, crude oil, natural gas, and uranium (for nuclear-generated electricity). As a result, the input from non-energy sectors to "Mining and Quarrying" is distributed evenly among each of its component energy resources, regardless of their very different production processes. In this case, DIO assumes that direct energy consumption (represented by E) is an exogenous input to the analysis, unaffected by flows from non-energy sectors.

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[3] We note that while DIO can theoretically trace energy flows to their points of production, in practice it has not been used in the global MRIO context due to data limitations.

However, this assumption is erroneous if an energy system relies on one type of resource more than the others and/or if the system transitions away from a dominant energy resource, say coal, towards another, such as natural gas or renewable energy.

3.2.3 Hybrid Input-Output Analysis (HIO)

HIO allows for more explicit tracking of direct and indirect energy flows than DIO. This is done by directly incorporating rows and columns for energy resources into the underlying financial transactions matrix (Z) thereby creating a hybrid-unit transactions matrix (Z^*) as illustrated in Figure 8d. Note that in HIO the underlying matrices expand to consist of $(n+p)u$ rows by $(n+p)u$ columns. Consequently, Z^* can be deconstructed into four submatrices, each with different units:

$$\mathrm{Z}^* = \begin{bmatrix} \mathrm{E}_{\pi} & \mathrm{E}_{\tau} \\ \mathrm{Z}_{\theta} & \mathrm{Z}_{\phi} \end{bmatrix}$$

[Equation 3.5]

Following the mathematical notation of Guevara and Domingos (2017), E_{π} represents the flow of energy to energy sectors, and E_{τ} represents the flow of energy to non-energy sectors (Guevara and Domingos, 2017).[4] The submatrix Z_{θ} represents the

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[4] θ here represents a generalized flow from an energy sector to a energy sector; τ represents a generalized flow from an energy sector to a non-energy sector.

monetary flow from non-energy sectors to the production of energy resources, and the submatrix Z_{ϕ} represents the flow from non-energy sectors to non-energy sectors. The transactions matrix in DIO would therefore be $[\mathrm{Z}_{\phi}]$, a subset of the HIO transactions matrix.[5] The rest of the mathematical framework is the same as the conventional IO analysis:

$$\mathrm{A}^{*} = \mathrm{Z}^{*}\widehat{x^{*}}^{-1}$$

[Equation 3.6]

Where $\widehat{x^{*}}^{-1}$ is the diagonalized inverse of a hybrid total output vector of length $(n + p)u$, and matrix A^{*} has the same dimensions as Z^{*}. A^{*}, which is functionally equivalent to the direct requirements matrix used in both conventional IO and DIO analyses, can also be decomposed into submatrices, each with a different unit:

$$\mathrm{A}^{*} = \begin{bmatrix} \mathrm{A}^{*}_{\pi} & \mathrm{A}^{*}_{\tau} \\ \mathrm{A}^{*}_{\theta} & \mathrm{A}_{\phi} \end{bmatrix}$$

[Equation 3.7]

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[5] For each region of the R regions, the submatrix $[E_{\pi} \quad E_{\tau}]$ has P rows

The submatrix A^*_π has units of TJ/TJ, A^*_τ has units TJ/USD, A^*_θ has units USD/TJ, and A_ϕ has units USD/USD. Finally, the total hybridized requirements matrix is given by:

$$L^* = (I - A^*)^{-1}$$

[Equation 3.8]

With the structure of the units in L^* being the same as that in A^*.

Thus, HIO in the global context requires data on region- and resource-specific energy production, domestic transactions of these energy resources, and bilateral transactions of these energy resources. It also requires information on the use of non-energy sector output for energy production, which as mentioned already has historically been a prohibitive obstacle in transitioning from DIO to HIO. In this study, we compile the granular data needed for HIO in a database we call the Hybridized Option for Modeling Input-output Energy Systems or HOMIES.

3.2.4 HOMIES

HOMIES traces direct and indirect energy flows through the global economy using the HIO approach. As mentioned previously, direct energy is what is used to produce a good or service, while indirect energy is "embedded" in goods and services during their production (Figure 9). We further define indirect energy here as energy embedded in the second or later stages of producing a good or service consumed by final demand. This embedded energy can either be from primary energy directly consumed in the first stage of the production process, or from primary energy used to generate secondary energy, e.g. electricity, that then gets used in the second or later stage of production (Figure 9). Whereas direct energy is measured and recorded in underlying IO matrices (e.g. Z and A matrices in Equation 3.2), indirect energy is estimated using matrix L (in Equation 3.3). Energy flows going to final demand will be classified as direct or indirect based on whether the last stage in the production process used direct or indirect energy (Figure 9).

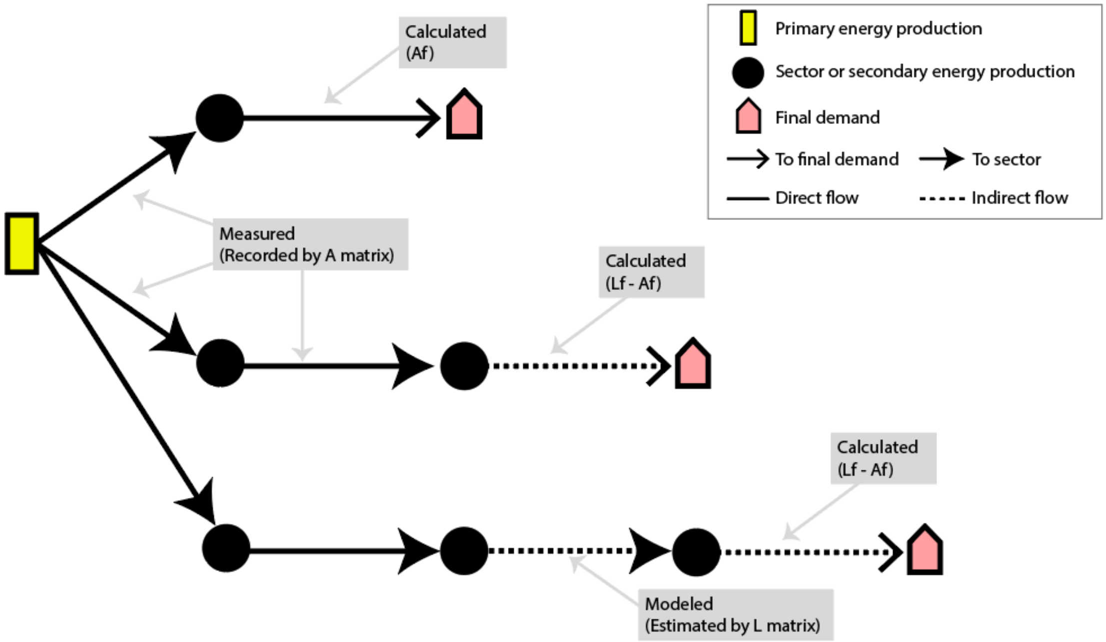

Figure 9. Illustrative example direct vs. indirect energy flows in HOMIES. The top flow represents a direct energy flow from primary energy production (the energy "source") to final demand (the energy "sink"). The energy flow is direct because it has been embedded in fewer than two stages of production before reaching final demand. The middle flow represents an indirect energy flow. The energy is indirect because it has undergone at least two transformations (either embedded in a good or service, or transformed into secondary energy) before reaching final demand. The bottom flow represents an indirect energy flow that undergoes three transformations before reaching final demand. The number of transformations will change with the length of the product's supply chain.

We note here that the direct energy flows (Af) and indirect energy flows (Lf) are derived by multiplying the *energy component* of the A^* and L^* matrices from Equations 3.7 and 8. Direct energy flows are thus calculated as the following:

$$x_{directenergy} = A^* f = \begin{bmatrix} A^*_{\pi} & A^*_{\tau} \\ 0 & 0 \end{bmatrix} f$$

[Equation 3.9]

Where we set non-energy flows to 0 and multiply the technical coefficients (i.e. energy intensities) by final demand. We calculate indirect flows by calculating total energy flows (replacing L* for A* in Equation 3.9) and then subtracting them by $x_{directenergy}$.

We build HOMIES using Eora because it currently includes greater spatial disaggregation and temporal breadth than other MRIOs (Moran and Wood, 2014). More specifically, Eora tabulates financial flows among 26 sectors in 189 countries from 1990 to 2015 and includes six final demand "sinks" as well as a direct energy input matrix (E in Section 3.2.2) for each year (Lenzen et al., 2013). In addition to the 26 sectors represented in Eora, we incorporate 13 additional rows and columns to represent specific energy types. These include seven primary energy resources and six secondary energy resources. The primary energy resources are: bioenergy, coal, crude, natural gas, nuclear (uranium), hydro (potential energy), and renewables. Here, renewables are defined as solar, wind, and geothermal energy. Hydro and bioenergy are given their own categories to better align energy databases with agricultural and electricity data. We provide further detail on these data in Section 3.2.4.1. The secondary energy resources are: combustion-based electricity, hydro-generated electricity, nuclear-generated electricity, renewables-based electricity, refined petroleum, and losses. We have included a list of all represented regions, countries, non-energy sectors, and energy types in the Supplementary Material (Sections 1-4).

Data on the domestic flows of direct energy are derived from the International Energy Agency (IEA) World Energy Balances database (WEB) (IEA, 2014). Of the 189 countries represented in Eora, we analyze the 136 that can also be found in WEB.[6] This database includes the production of each energy type (in TJ), as well as the consumption of that energy by sector (e.g. electricity used in domestic textile manufacturing). However, it does not include bilateral information, i.e. the flow of energy from energy-*producing* country to a different energy-*consuming* country. This information is instead recorded in the BACI trade database, a harmonized compilation of UN COMTRADE trade data (Gaulier and Zignago, 2008). The latter data, which are given in tonnes and USD amounts, are converted to energy flows using each country's unique annual average net calorific value (in TJ/kt) for every type of primary energy as published by the IEA (IEA, 2018c). We assume that the net caloric values (NCVs) are constant across all years of the study. By combining WEB to BACI, we are able to capture the flow of primary energy from its production through its domestic transformation to secondary energy and its consumption both domestic and abroad.

The data compilation process for HOMIES can be broadly divided into two steps. The first step is to scale physical energy flows among the 26 sectors and 13 energy types. The second step is to scale monetary flows among the sectors and energy types. Each

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[6] We assume a global economic system consisting of only these 136 countries and do not include additional flows for exports to/imports from countries outside of this list.

step has a domestic component and an international trade component. In the former, we compile domestic transactions (e.g. Russian natural gas energy used in Russian machinery manufacturing). In the latter, we compile all bilateral transactions (e.g. Russian natural gas energy used in German machinery manufacturing). The resulting matrix is matrix Z^* in Section 3.2.3.[7]

3.2.4.1 Scaling physical energy flows

For each country in each year, Eora represents energy inputs into sectors but does not specify the country in which this energy was produced. HOMIES builds on Eora by adding bilateral energy flows that specify the type of energy, the producing country, the consuming country, and the consuming sector. WEB provides data on the flow of specific energy resources into sectors that align closely with the 26 sectors represented in Eora. Among the sectors in WEB are 15 that directly correspond to those in Eora. Six of the remaining sectors in Eora fall under the larger umbrella sector in WEB titled "Commercial and Public Services".[8] Consequently, we divide the energy going to the single WEB group into sub-flows that go into the six related Eora sectors, with the energy in these sub-flows being scaled based on each of the latter sectors' contribution to

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[7] An illustrative representation of HOMIES as it relates to the mathematical framework laid out in Section 3.2.3 can be found in the Supplementary Material.

[8] The 6 Eora sectors are: Maintenance and Repair (15), Hotels and Restaurants (18), Post and Telecommunications (20), Financial Intermediaries, and Business (21), Public Administration (22), and Education Health, Other Services (23)

a country's total economic output (in USD).[9] The remaining five sectors in Eora have no corresponding sector in WEB.[10] To overcome this, we exploit the Eora database's own energy use matrix (E in Section 3.2.2). This matrix includes the flow of energy resources into the 26 sectors. We use WEB to calculate, for each country and for each energy resource, the fraction of energy demand that is met domestically. We then multiply these fractions with E to build the domestic component of energy flows into the five remaining sectors.[11] For the international trade component, we use BACI data to divide the imports of each energy type into 26 sectors. We assume that countries use their imported energy proportionally to the ways they use their domestically-produced energy. A table further detailing our correspondence between WEB and Eora sectors can be found in the Supplementary Material (Section 2).

To scale physical energy flows going into producing bioenergy, data from the FAO (Crop Production Database) and the IEA (Renewables and Waste Database) are used to calculate the fraction of agricultural output from each country used for bioenergy production (FAO, 2018; International Energy Agency, 2017b). We first calculate the amount of agricultural output (in tonnes) that is required to meet bioenergy

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[9] Let's say sectors A, B, C, D, E, F comprise "Commercial and public services", and output from each sector A is described as oA. The energy flow to sector A would be equal to the energy flow to "Commercial and public services" multiplied by [oA/(oA + oB + oC + oD + oE + oF)].

[10] The 5 Eora sectors are: Wholesale Trade (16), Retail Trade (17), Private Households (24), Others (25), Re-export and Re-import (26)

[11] We do not use this method to scale other the other 21 sectors because we aim to minimize assumptions regarding the energy system. We use actual data when actual energy flow data are available.

demand (in TJ) for each country and year. Bioenergy demand (in TJ) is given in the Renewables and Waste Database for each country, year, and bioenergy commodity (e.g. biodiesels). We multiply demand of each bioenergy commodity by its corresponding mean conversion efficiency and then divide the product by the commodity's mean energy content (in TJ/tonne). We have included a table with these values for the represented bioenergy commodities in the Supplementary Material. From here, we are able to take the fraction of agricultural output from the Crop Production Database (in tonnes) that is used for bioenergy production (now also in tonnes). We then multiply this fraction by the flows of energy going into the Agricultural sector as a whole to yield the share consumed in bioenergy production.

The energy used to extract crude oil and natural gas is combined in WEB under "Oil and Gas Extraction". We divide this flow into separate crude oil and natural gas components by calculating the fractions of each country's production of the two resources using additional data from the IEA. These fractions are then in turn used to scale the amounts of energy going into "Oil and Gas Extraction" to yield the energy the country consumed producing oil and producing natural gas.

The energy inputs used to mine coal, refine petroleum, and generate electricity (for combustion, hydro, and nuclear based generation) are explicitly represented in WEB and do not need to be scaled. National use of input energy from uranium, solar and wind resources for generating electricity on the other hand are not included in WEB. We estimate the amounts of these primary energy types with a back-calculation that uses efficiency data for existing generation technologies provided by the U.S. Energy Information Administration (U.S. Energy Information Administration, 2018, 2011). For uranium, we first compile nuclear-based electricity generation by country and year. We assume that the only energy use for uranium is electricity generation. We then estimate the amount of nuclear energy required to generate a TJ of nuclear electricity, assuming an average efficiency of 35% for nuclear power plants. We link this to the World Mining Database to estimate domestic production. Finally, we link the remaining amount to the BACI database to estimate the bilateral trade flows used to meet energy demand. This procedure, as well as our correspondence table for relating IEA and HOMIES energy types, can be found in the Supplementary Material (Section 6).

3.2.4.2 Scaling monetary flows to energy production

While Eora already maps out monetary flows between sectors and their energy inputs, it does not track the flow of money from all the sectors that goes into producing/extracting primary energy. However, this information is critical for establishing bidirectional flows of embodied energy between energy and non-energy producing sectors. This information is estimated in HOMIES by: (i) identifying which Eora sector includes the production of a given primary energy type (e.g. the sector “Mining and Quarrying” includes coal mining); (ii) estimating the fraction of the sector’s total output that goes into producing the energy type; and (iii) multiplying this fraction by the total monetary flow going into the sector to yield the share used to produce an energy type. Note that this approach is identical to how we scale the physical energy flows into producing primary energies, except in this case we are estimating monetary flows going into the production.

For bioenergy, the fraction of agricultural output used to produce bioenergy is multiplied by the monetary flows into “Agriculture”. Coal, crude oil, natural gas, and uranium on the other hand all fall under “Mining and Quarrying”, so the respective proportions of the total monetary flow going into this sector need to be determined for each energy type, which we do using historical data from the World Mining Database (Federal Ministry for Sustainability and Tourism, 2019). This database includes mining production by resource, country, and year, allowing for the determination of the fraction of total mining that went into extracting each of the four primary energies (i.e. coal, crude, natural gas, uranium). These fractions are then weighted by the export price of each resource as given in the BACI trade database. This weighting is done to reflect the varying costs of producing the different types of resources (e.g. it is less costly to mine for coal than it is to mine for uranium, and labor costs can vary widely by country). The resulting fractions are then multiplied by monetary flows going into “Mining and Quarrying”, thereby dividing the flow into five separate sub-flows: one each for the production of coal, crude oil, natural gas, uranium, and non-energy mining and quarrying activities.

Petroleum production (i.e. crude oil refining) falls under the Eora sector "Petroleum, Chemical, and Non-Metallics". WEB separates out the amounts of electricity (in TJ) used by oil refineries vs. chemical manufacturing and non-metallics manufacturing, so dividing the electricity used in oil refining by the total electricity used across all three types of manufacturing gives the fraction used to produce petroleum products. Multiplying this fraction by the monetary flows going into "Petroleum, Chemical, and Non-Metallics" divides the flow into its energy (refining) and non-energy (chemical and non-metallic) components. In doing this, we assume electricity consumption is an adequate proxy for other capital inputs.[12]

In Eora, electricity is included in the "Electricity, Gas, and Water" sector. This sector does not directly correspond to any sector in WEB, preventing us from using the latter to separate out the energy component of the former. The OECD, however, publishes detailed supply-use tables (the Z matrix in Section 3.2.1) for 45 countries in which electricity, gas, and water are broken out. We use these tables to estimate the fraction of monetary input to the three utilities that goes into electricity, doing this calculation for each of the 45 countries. We then use k-means clustering to extrapolate

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[12] e.g. the proportion of electricity used for petroleum compared to chemicals/non-metallics is equal to the proportion of steel used for petroleum compared to chemicals/non-metallics.

the electricity fractions for the 45 OECD countries to the 136 countries included in Eora and HOMIES. Finally, we multiply each country's electricity fractions by the monetary flows in Eora going into the country's "Electricity, Gas, and Water" sector to yield the sub-flow directed towards electricity generation.

Since electricity is generated from primary energies, its monetary flow is itself sub-divided into monetary flows to fossil fuel electricity generation, nuclear electricity generation, hydro electricity generation, and renewables-based generation.[13] To calculate these sub-flows, the electricity generation mix is determined for each country in each year. Then, because some forms of electricity generation are more expensive than others (e.g. renewables vs. fossil-fuel generation), we further scale the monetary flow to each generation type using Levelized Cost of Electricity (LCOE) data from the U.S. National Renewable Energy Laboratory (NREL), the Energy Information Administration (EIA), and the Federal Energy Regulatory Commission (FERC), as well as from existing literature (Feldman et al., 2015; McNerney et al., 2011; U.S. Energy Information Administration, 2019c; Wiser and Bolinger, 2017). For each year, the mean LCOE, by generation type, are converted to weights.[14] Finally, the monetary flow that goes toward

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[13] For the purposes of this analysis, we do not further divide fossil fuel generation into coal, natural gas, and crude oil.

[14] This is calculated by dividing the mean LCOE for a given generation type (e.g. fossil fuels) by the sum of mean LCOE across generation types.

electricity generation in Eora are multiplied by these weights to further divide them into flows by generation type. [15]

3.2.5 Application of HIO and HOMIES in this study

This analysis focuses on direct and indirect energy flows originating from the production of coal, crude oil, natural gas, uranium, and renewables (i.e. solar, wind, geothermal). By tracing embodied energy flows from their primary energy sources to their consumption sinks, we are able to break down: (i) whether the energy going into a sector leaves in the sector's output as direct or indirect energy, (ii) where both direct and indirect energy are sourced, and (iii) where direct and indirect energy are demanded. This information is illustrated conceptually in Figure 10 for a hypothetical country (Country A) that trades with all other countries grouped as "rest of world" (ROW).

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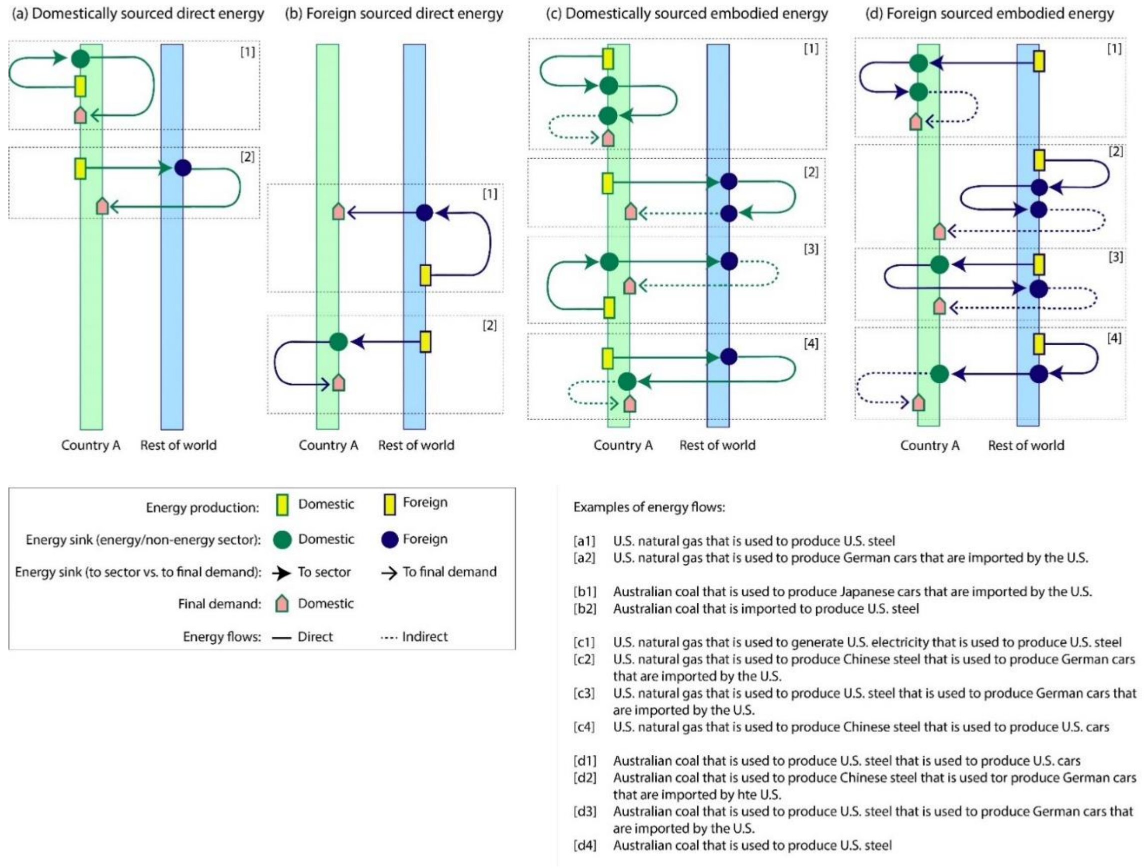
[15] While this is a "best-case" price, we do not use the magnitude of the LCOE per se. We simply care about the LCOE of specific generating resources relative to one another. We are therefore working with the assumption that while the LCOE may change by region, the relation of various LCOE will remain generally consistent.



Examples of energy flows:

[a1] U.S. natural gas that is used to produce U.S. steel
[a2] U.S. natural gas that is used to produce German cars that are imported by the U.S.

[b1] Australian coal that is used to produce Japanese cars that are imported by the U.S.
[b2] Australian coal that is imported to produce U.S. steel

[c1] U.S. natural gas that is used to generate U.S. electricity that is used to produce U.S. steel
[c2] U.S. natural gas that is used to produce Chinese steel that is used to produce German cars that are imported by the U.S.
[c3] U.S. natural gas that is used to produce U.S. steel that is used to produce German cars that are imported by the U.S.
[c4] U.S. natural gas that is used to produce Chinese steel that is used to produce U.S. cars

[d1] Australian coal that is used to produce U.S. steel that is used to produce U.S. cars
[d2] Australian coal that is used to produce Chinese steel that is used tor produce German cars that are imported by hte U.S.
[d3] Australian coal that is used to produce U.S. steel that is used to produce German cars that are imported by the U.S.
[d4] Australian coal that is used to produce U.S. steel

Figure 10. Illustrative example of the energy flow calculation for hypothetical country A. (a) Direct flows of energy sourced domestically. (b) Direct flows of energy sourced abroad. (c) Indirect energy that is sourced domestically. (d) Indirect energy that is sourced abroad. Green lines and shapes represent production and flow of domestically-sourced energy. Blue lines and shapes represent production and flow of energy sourced abroad. The shapes and lines used in Fig. 3 directly correspond to those used in Fig. 2.

Figures 3a and 3b represent direct energy flows to Country A, while Figures 3c and 3d illustrate indirect energy flows into the country. Green outlines and arrows follow the flow of domestically-sourced energy whereas blue outlines and arrows follow the flow of energy sourced abroad. Again, direct energy flows are flows of primary energy that have undergone fewer than two transformations before reaching final demand. An example would be natural gas used for cooking in the final stage of producing prepared food. Indirect energy flows include the energy consumed at all stages leading up to the assembly of the final product. For prepared foods, this may include the energy used to plant, fertilize and harvest crops, transport the crops to a processing facility, and then transport the processed crops to a restaurant.

Note that domestically-sourced energy can be used abroad and re-imported. For example, coal extracted in the United States may be imported by China and used to produce steel that, in turn, is imported by the United States. In this case, the United States would be importing energy originally in its coal export that is now direct energy in the Chinese steel. Alternatively, the United States' coal that is exported to China could be used to produce steel that China then exports to Japan, where the steel is used to manufacture cars that are exported to the United States. In this case, the returning energy flow to the United States would be as indirect energy because the original energy in the coal would have been incorporated into more than one production process.

3.2.6 Measuring energy security

In this study, we assess energy security at the global, sectoral, and national levels using two metrics. The first is import dependence, which we calculate by dividing imported energy consumption by total energy consumption. In the energy security literature, import dependence is used to measure how vulnerable a country's energy system is to foreign shocks (Cohen et al., 2011; Gupta, 2008; Le Coq and Paltseva, 2009). Here, we apply import dependence to both direct energy and indirect energy. Once primary energy is transformed and embedded into goods and services, these products carry embedded primary energy when they are exported. The import dependence of indirect energy estimates the fraction of this embedded energy that was sourced abroad. If this value is low, it means the country's domestic primary energy resources are able to sustain global production processes that are required to meet its final demand. On the other hand, if this value is high, the country relies on global production processes that are fueled primarily by foreign resources. It is therefore more vulnerable to energy shocks abroad.

The second metric we use is the Herfindahl-Hirschman Index (HHI). HHI is used extensively to measure the size of firms in an industry and the competition among them (The United States Department of Justice, n.d.), but the index is also used as a metric of energy security (Cohen et al., 2011; Gupta, 2008; Le Coq and Paltseva, 2009; Löschel et al., 2010; Månsson et al., 2014). The HHI is defined as:

$$HHI_{ej} = \sum_i s_{ej}^2$$

[Equation 3.9]

Where s_{ej}^2 represents the squared fraction of either imports or exports in fuel e going from nation i to nation j. The HHI ranges between approximately 50 and 10,000.[16] The higher a country's HHI, the more it relies on a few exporters/importers for a particular energy type, while the lower a country's HHI, the more exporters/importers it is working with and the more equal each exporter's/importer's fraction. For instance, if a country imports 90% of its oil from country A and 10% of its oil from country B, the HHI of the importer portfolio would be equal to (90^2+10^2) = 8,200. Alternatively, if the country imports 10% of its oil from each of 10 different exporters, the country's HHI would equal $10(10^2)$ = 1,000. It is important to consider HHI in conjunction with import dependence and not as a standalone metric, as HHI alone only addresses the portion of a country's energy use that comes from imports. This alludes to the difference between vulnerability (i.e. conditions that can exacerbate the impact of a trade disruption) and exposure (i.e. the scale of impacts from a trade disruption). HHI can address vulnerability while import dependence can address exposure (Wellesley et al., 2017).

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[16] We assume a minimum HHI of about 50 given that there are about 200 potential trade partners for each country, and if each of these partners receive an equal fraction of the country's trade, we would have an HHI equal to $200 \times \left(\frac{100}{200}\right)^2$, or 50. In the parentheses, we divide 100% by the number of linkages (200): $\frac{100}{200}$

3.2.7 Assumptions and limitations of this study

When building HOMIES, we required several underlying assumptions where corresponding data were not available. First, we assume that countries use imported energy resources proportionally to how they use domestic energy resources. This essentially means that in HOMIES, countries draw from a resource pool that includes both domestic and imported energy.[17] Secondly, we assume that electricity requirements by a subsector are proportional to non-energy requirements by that subsector. This only applies to the instance in which we seek to divide out the energy component of the "Petroleum, Chemical, and Non-metallics" sector in Eora. Third, we assume that renewable primary energy sources (i.e. wind, solar, geothermal) do not require non-energy sector input. Electricity generated from renewable energy, on the other hand, does require input from non-energy sectors. For example, solar primary energy is used to generate electricity, but the sun does not require industrial input to produce this energy. Fourth, we assume that LCOE is proportional to the relative capital intensities of electricity generation by resource. This means that, for a given year, the monetary inputs required to produce a TJ of electricity will be divided into the generation types (e.g. fossil fuels, renewables, hydro, nuclear) based on the LCOE. This reflects the fact

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[17] To validate this assumption, we compared the prices of imported energy and domestic energy and found that they are approximate. For instance, the United States' average imported crude oil price in HOMIES is \$53.16/bbl in 2015, compared to \$46.17/bbl for domestically produced crude (U.S. Energy Information Administration, 2019d). In China, HOMIES estimates an average import price of \$73/tonne for coal compared to \$83/tonne for domestically produced coal (Stanway et al., 2015).

that, until recently, capital costs for solar/wind have been significantly higher than those of conventional resources like coal and natural gas.

We note that building HOMIES required considerable data compilation and we recognize that our estimates of embodied energy undoubtedly have uncertainty stemming from measurement error, or error that we cannot quantify. We have attempted to address these uncertainties by validating data across sources at each stage of the data compilation. Figures related to this validation can be found in Section 8 of the Supplementary Material. We find that the underlying energy input data that are in Eora do not always align with our input data derived from WEB. One likely reason for this is differences in the aggregation of industries to fit the 26-sector Eora setup. Other reasons include inconsistencies in measurement reporting (both in terms of accuracy and completeness), different approaches used to measure and/or estimate energy consumption, variation in the degree of independent verification of reported measurements, and differences in the sources of the underlying data (e.g. using input-output accounts from national statistical agencies vs. using proprietary data from industry). Discrepancies in embodied energy estimates are therefore not only reflective of differences in research objectives and methods, but also data interpretation and even the data themselves.

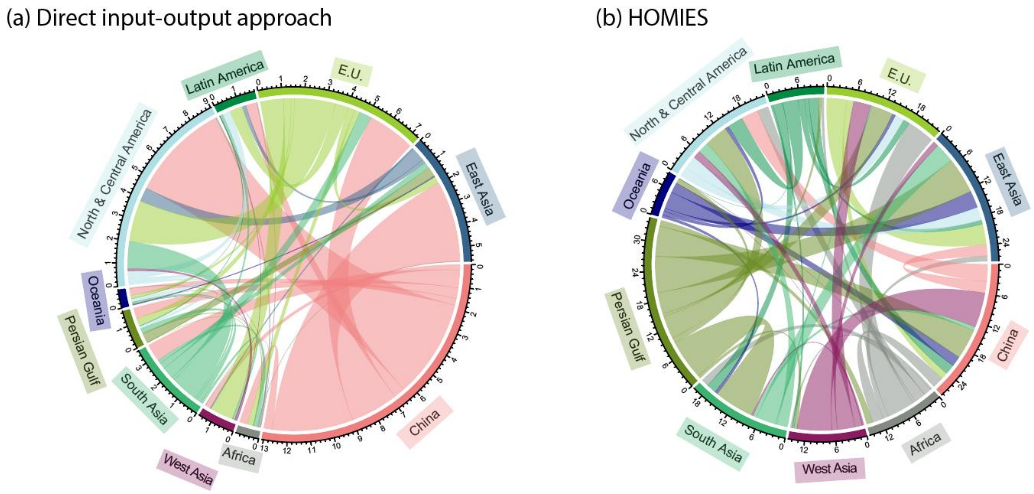
Furthermore, while HOMIES provides a more explicit regional representation of energy production and inputs than DIO models, our method still suffers from issues common in all IO analyses. In particular, we are still aggregating industries to a high-level and therefore do not address the heterogeneity of industry and firm behavior within each sector. This heterogeneity presents interesting questions for future research, but is beyond the scope of our analysis here.

3.3 Results and Discussion

The main objectives of this study are to (i) compare the uses of direct and indirect energy, thereby identifying areas where they diverge, and (ii) examine these differences with respect to energy security metrics. A country may seem energy secure in terms of direct energy, but if it relies on one or more critical products that are manufactured abroad, then it is also energy import dependent, albeit indirectly. Using HOMIES, we can expand our understanding of energy security beyond the immediate production and use of energy in a given country or sector. We first compare the global energy trade network resolved by HOMIES to the network resolved by existing methods (i.e. DIO). We then use HOMIES to compare the import dependence of direct and indirect energy flows at the global and sectoral level. Finally, we estimate key energy security metrics at the national level and discuss mechanisms that drive differences in direct and indirect energy security.

3.3.1 Implicit energy linkages

Because HOMIES traces energy flows from the point at which primary energy resources are first produced rather than first consumed, energy flows mapped by HOMIES will differ from the flows mapped by DIO. This is illustrated in Figure 11, which compares the embodied energy flows mapped by DIO and HOMIES. In these chord diagrams, countries have been aggregated into regions to make the contrast between the two methods clearer.[18]


(a) Direct input-output approach

(b) HOMIES

Figure 11. Embodied energy flows through the global economy in 2015. Values are produced using DIO (a) and HOMIES (b). Colors correspond to source regions of embodied energy flows, i.e. direct + indirect energy exports in goods and services. The sources in the DIO approach are countries that first *consume* primary energy, whereas the sources in HOMIES are the countries that *produce/extract* the primary energy. Note that the DIO diagram is similar to that produced by Chen et al. (2018) but different because the latter was constructed for communities of trading countries that those authors defined using network analysis.

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[18] A table corresponding region to countries can be found in the Supplementary Material.

In the DIO chord diagram, the biggest source of embodied energy is China, followed by the E.U. and South Asia. This is because these regions are the world's largest net exporters of goods and services, many of which are manufactured by economic sectors that consume massive amounts of primary energy. In the HOMIES result, however, only a fraction of the embodied energy in Chinese exports originates in China. Instead, primary energy in these exports is mostly from the Persian Gulf and West Asia. In fact, according to HOMIES, the Persian Gulf, Africa, and West Asia regions are the largest sources of primary energy embodied in the global economy.

Because HOMIES explicitly models the link between the extraction of primary energy and its transformation into embodied energy, our analysis shows energy linkages between countries that do not trade directly in primary energy resources. This is exemplified in the flow of indirect energy into the United States. When we consider primary energy from the point of extraction (i.e. use HOMIES), we find that there is a significant energy flow from Russia to the United States.[19] This is because Russian energy, primarily in the form of natural gas and crude oil, is used in Europe and China to produce goods and services. When these goods and services are exported to the United States, so too is the energy embodied in them.

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[19] We present a figure related to these results in the Supplementary Material.

We estimate that, on average, 23% of world trade in embodied energy was conducted by countries that do not have apparent energy trade linkages.[20] This percentage indicates the degree to which national economies rely on energy systems outside of their direct trade networks, and suggests that the embodied energy importers represent a significant component of the global energy system. Furthermore, these implicit energy linkages present significant implications for global energy security. First, the outsourcing of economic activity abroad can be viewed as an energy security strategy, especially when a country does not have energy resources of its own. However, when an importer does not produce goods and services domestically, it is more dependent on foreign energy systems to meet its final demand. If a foreign energy system that powers the production of a critical good or service (e.g. steel) experiences an energy shock, this shock will reverberate through the supply chain to the importer of the product. Thus, our understanding of energy security as the uninterrupted supply of affordable energy must be adjusted to include both direct and indirect energy flows. Second, energy flows into a country can be categorized as being sourced (i) domestically, (ii) by an existing trade partner, or (iii) by a country with which it does not have direct trade ties. Energy flows from (iii) are often beyond the scope of the country's policy leverage, exposing it to a potential energy, economic, or societal shock. For

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[20] This was determined by summing the energy flows among countries that do not trade in primary energy, and dividing it by that year's sum of embodied energy flows among all countries.

example, in the case above, the United States is a third party to energy trade discussions among Russia, Europe, and China. However, it is dependent on the stability of these energy linkages in order to maintain critical supply chains, such as those that source inputs used in the U.S. to produce automobiles, medical equipment, and electronic products. These supply chains underpin the U.S. economy because it is used across economic sectors. The energy security of the supply chains, however, is contingent on the stability of foreign energy systems because they rely upon a globalized production process.

3.3.2 Global energy security metrics

We next apply HOMIES towards understanding the overall reliance of the global economy on imports of direct vs. indirect primary energy. We calculate global import dependence of direct and indirect energy by aggregating all country-level measurements of these two ratios. Throughout this aggregation, we keep track of where the direct and indirect energy in every bilateral transaction of a good or service was originally sourced. The results are shown in Figure 12a and 12b, respectively. In both stacked bar graphs, the total height of the bars is the total direct or indirect annual demand for these energies by the global economy.[21] We note that these figures reflect the direct and

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[21] We estimate the footprint by multiplying matrix L^* by a vector of final demand f_j. If we wanted total energy consumption of a country, we would multiply L^* by the total output of the underlying transactions

indirect flows of primary energy. Figure 12a, which illustrates direct energy flows, shows that natural gas makes up nearly half of total direct energy demand. The reason crude oil is not the largest source of primary energy is that it must first be transformed into a secondary energy resource (e.g., gasoline and diesel) before it can be used by any intermediate sector (e.g. transportation). While the same holds for pretty much all other forms of primary energy, natural gas can be consumed directly and is used as a feedstock and/or heating source for a range of final demands. Thus, excepting these cases for natural gas consumption, primary energy that is used to meet final demand will only be reflected in the indirect energy flows illustrated by Figure 12b, leading indirect primary energy demand to be much larger than direct primary energy demand. For instance, world imports of crude oil reached 43.1 million barrels/day in 2015 (Organization of Petroleum Exporting Countries, 2016). In HOMIES, all of this energy constitutes just 25.3% of that year's indirect energy imports.

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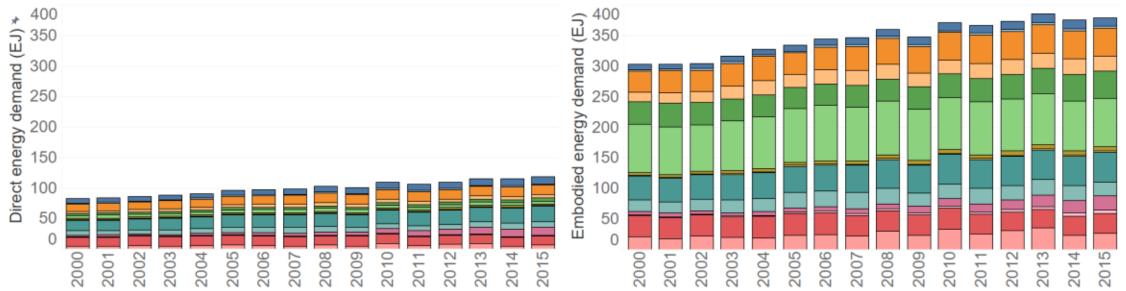
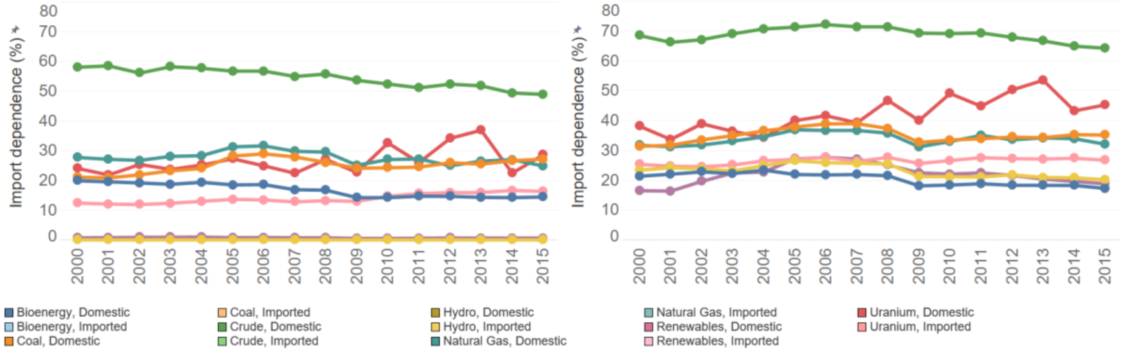
matrix. However, this would no longer be consumption-based accounting. Recall that the aim in calculating the energy footprint is to attribute energy consumption to the final end-use sink.



(a) Direct energy

(b) Indirect energy



(c) Direct import dependence

(d) Indirect import dependence

Figure 12. Global energy consumption and import dependence, 2000-2015. (a) illustrates global direct energy demand (A[1]-A[2] and B[1]-B[2] in Figure 10); (b) illustrates global indirect energy demand (C[1]-C[4] and D[1]-D[4] in Figure 10). Lighter hues represent the components of each resource footprint that were originally sourced abroad (i.e. not in the country that ultimately uses it). Darker hues represent the component that was originally sourced domestically. (c) illustrates the direct net import dependence by resource, while (d) illustrates the indirect net import dependence.

Our results indicate that, on average, 23% of the direct energy that countries consume is derived from primary energy resources sourced abroad. For indirect energy consumption, the average is nearly two times greater at 44%.[22] However, the import dependence of indirect energy varies by primary energy resource. For example, 69% of

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[22] This is the average across 2000-2015

the crude oil in the indirect energy consumed by all nations comes from foreign sources, on average. This oil was largely produced in the Middle East and North America, which together comprised 51% of global production in 2015 (BP Energy Economics, 2019). How this energy is subsequently exported as indirect energy varies by region, however. In the case of the Middle East, most of the crude oil produced is exported as primary energy (64% in 2015) (Organization of Petroleum Exporting Countries, 2016), which is then transformed into secondary energy in the form of refined petroleum products made outside the Middle East. A large fraction of these petroleum products, which are a form of *direct* energy, are then exported and used in yet more countries to make additional goods and services that now contain Middle Eastern oil in the form of indirect energy. In contrast, most of the crude oil produced in North America is refined and consumed in the region, contributing to the vast majority of the continent's indirect energy being domestically sourced (82% in 2015). And the fraction of North American produced goods and services that are then exported abroad contain North American crude oil.

Natural gas is different. Some 66% of the global requirement for this form of primary energy is sourced domestically. At least through 2015, this difference was due to the fact that natural gas exports were largely restricted to being moved through land-based pipelines, relatively few of which cross national boundaries. Oil on the other hand can also be moved by ship, a much more flexible form of transport that has greatly contributed to oil being a globally traded commodity.

A significant fraction of indirect energy comes from uranium, a form of primary energy that is only used to generate electricity, a secondary and thus indirect use of primary energy. Uranium ends up comprising a large part of global indirect energy consumption because of its very high specific energy (500TJ/tonne) and the low efficiency of nuclear power plants. Thus, while roughly a third or less of the energy in uranium gets embedded as indirect energy in goods and services, the amount of primary energy that went into producing that indirect energy is huge (U.S. Energy Information Administration, 2018). Relatedly, the spikiness to the uranium component of indirect energy import dependence (Figure 12d) stems from volatility in uranium markets and trading over the study period (Gaspar and Mayhew, 2018).

Our results show that the import dependence of both indirect energy from coal and natural gas has increased over the study period and, given the current state of the global energy economy, will likely continue doing so. For coal, this increase is driven by China's emergence into the global economy. Whereas China uses much of the direct coal energy it extracts domestically, its goods and services are increasingly exported to other countries. Consequently, China's indirect energy supply chain is increasing in magnitude and in breadth. For natural gas, the shale gas boom in the United States has led to an increase in indirect natural gas embedded in the goods and services the country produces. As the United States continues to export these goods and services, the natural gas component of their embedded energy will increase.

The divergence in direct vs. indirect import dependence, as well as the growth of the latter for coal and natural gas, signals vulnerabilities in the global energy system. It suggests that the global economy is more reliant on a stable primary energy market than we currently understand it to be. This is particularly significant for the supply chains of manufactured critical products like computers and automobiles. These supply chains have many production steps, each requiring different energy inputs. They are also highly globalized such that the steps may occur in different countries with drastically different energy systems. The importing country, in many cases, therefore relies on the energy trade structures of all countries in the supply chain while having little policy leverage outside its own borders. Potential exceptions to this are importers that have both abundant energy resources and a large capacity for producing their own goods and services, rendering them less vulnerable to unforeseen disruptions to this dependence. Even in these cases, however, it may take such importers time to develop and/or adapt domestic production facilities so as to make the effected goods and services.

3.3.3 Sectoral energy security metrics

The indirect energy import dependence of the global economy is driven by its non-energy sectors, which also can be assessed in terms of energy intensity. Direct energy intensity describes the per-unit energy use at the final stage of a supply chain. For example, this would include the primary and secondary energy (e.g. natural gas and electricity, respectively) that is used to manufacture a car. Indirect energy intensity, on the other hand, describes the sum of energy intensities (i.e. energy requirements per unit of output) that is used in all of the preceding links in the supply chain. This also includes the per-unit energy that is used in the supply chain of each of these links. In our car example, this would therefore include the direct primary and secondary energy used to produce the car radio, the energy used to mine the copper used in the radio, and so on. Recall that embodied energy is the sum of direct and indirect energy. Therefore, embodied energy intensities (i.e. direct + indirect intensities) will be significantly larger than the direct energy intensities we present below. The global averages for these are shown in Figure 13, where each sectoral intensity is further broken down into the fraction derived from domestic vs. foreign sourced primary energy.[23]

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[23] These were computed by calculating the annual direct and indirect energy intensities for each sector in each country, and then weighting these by each country's total economic output each year to arrive at a sector-by-sector weighted average for the world.

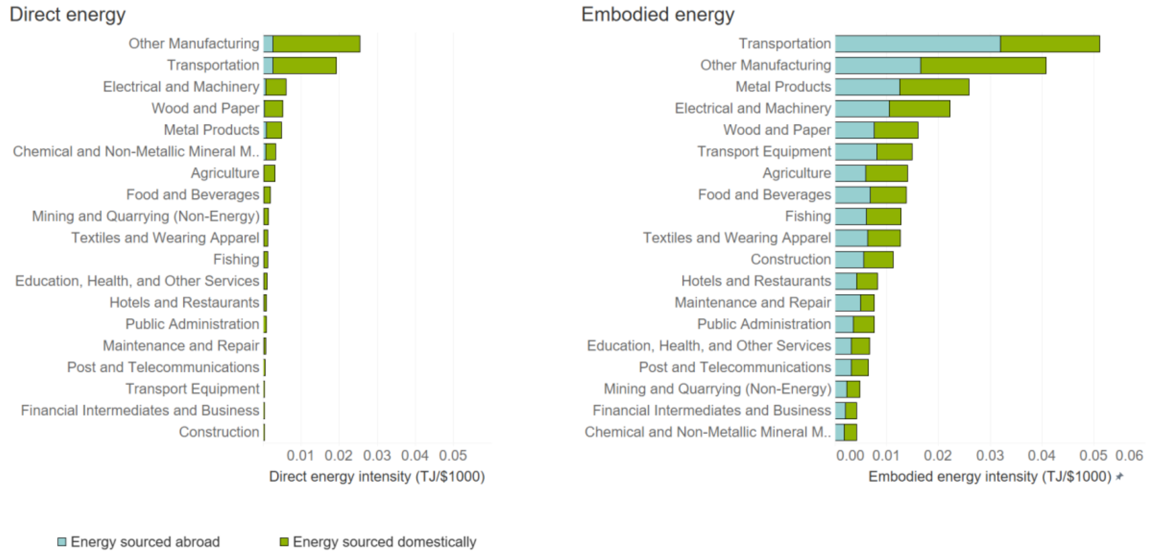

Figure 13. Global average energy intensity by non-energy sector. Colors represent whether the underlying energy resource was produced domestically (green) or abroad (blue). Bars are arranged in descending order of energy intensity.

The vast majority of sectoral direct energy intensities (85%) is ultimately derived from domestic sources of primary energy. Note that this percentage includes cases in which a country that exported primary energy re-imported a fraction of it used to produce a good or services from overseas without the product undergoing any further transformation (e.g. A[2] in Figure 10). Indirect energy intensities on the other hand involve a much greater fraction of primary energy sourced from abroad, with the average exceeding 50%. Unsurprisingly, this is particularly true of the transportation sector, which runs on refined petroleum products. While most countries have refineries and can produce their own petroleum products, all the refineries require crude oil as input. Crude oil is a primary energy exported by relatively few countries, the majority of which surround the Persian Gulf (U.S. Energy Information Administration, 2017). Consequently, as of 2015, not only did the global transportation sector have one of the highest indirect energy intensities (Figure 13b), but it was also the most reliant on indirect energy imports.

Further examination of Figure 13 reveals that when ranked by energy intensity, most sectors fall at or near the same ranking in terms of both direct and indirect energy intensities. There are, however, a subset of sectors that rank higher in indirect energy intensity than direct energy intensity, and vice versa. An example of the first type is transport equipment, which includes the manufacture of cars, planes, and maritime vessels. More than half of this sector’s indirect energy intensity (Figure 13b) is derived from primary energy extracted overseas. We interpret this to reflect the complex global supply chains relied upon by manufacturers of transport equipment. For instance, a car produced in Germany may involve steel imported from China, plastics from the United States, and copper from Chile. Each of these materials requires energy input in their countries of production, which itself may be extracted domestically or abroad. When all of these direct and indirect energy flows are considered, the energy intensity of the sector adds up and expands geographically. An example of the second type is chemical and non-metallic mineral products manufacturing. This sector ranks relatively high in direct energy intensity (Figure 13a) but last in indirect energy intensity (Figure 13b). As a result, this sector, at least globally, appears to be significantly less reliant on foreign sources of primary energy than just about any other sector.

3.3.4 Country-level energy security metrics

We now move to country-level dependencies on direct and indirect energy, which we assess in terms of import dependence (as previously defined), number of energy trade linkages, and the Herfindahl-Hirschman Index (HHI). The histogram in Figure 14a displays the distribution of import dependencies at the country-year level for direct (blue) and embodied (red) energy consumption between 2000-2015.[24] The dependencies range from 0% (all energy consumed was sourced domestically) to 100% (all energy consumed was imported). The plot shows that a majority of countries over most of the study period had a direct energy import dependence of <50%, but an indirect energy import dependence of >50%. Thus, even nations that were close to achieving energy independence in terms of direct energy still remained dependent on other countries' energy systems for indirect energy.

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[24] Each observation is an individual country in a given year

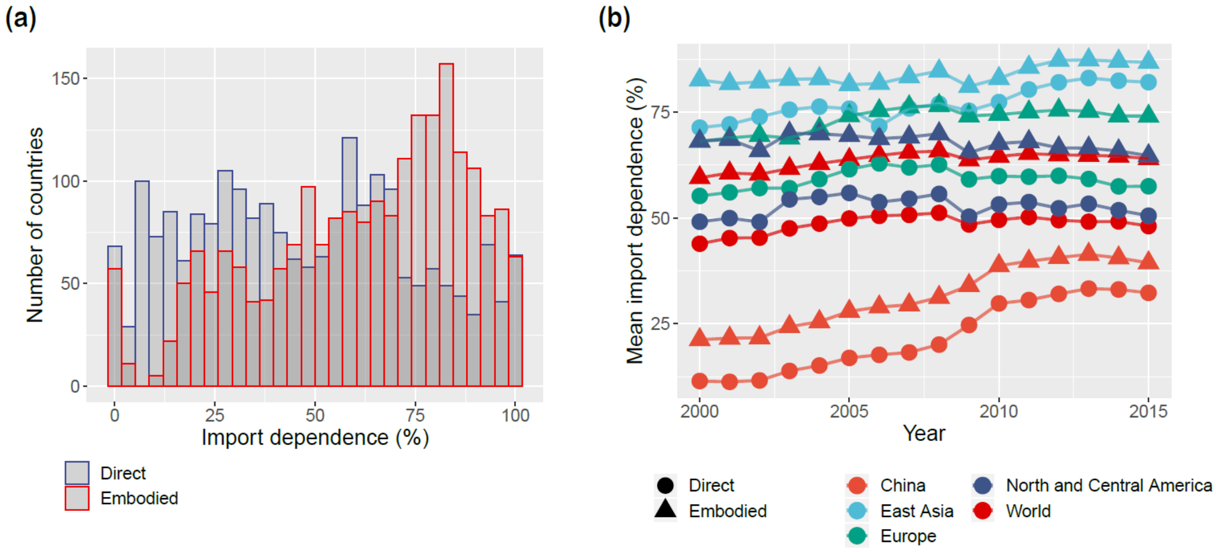

Figure 14. Import dependence between 2000-2015. The left panel (a) illustrates the distribution of import dependence (direct vs. embodied) at the country-year level. Import dependence generally increases (shifts right) for countries that consume more indirect than direct energy. The right panel (b) represents annual trends in regional import dependence (both direct and embodied). East Asia does not include China.

Trends in the mean import dependence of both direct and indirect energy have stayed relatively constant at the global level, but vary significantly by region. Year-on-year changes in import dependence are plotted in Figure 14b. The plot shows that China's import dependence of direct and indirect energy has increased markedly. North and Central America on the other hand have experienced a gradual decline in import dependence, largely due to the shale gas boom in North America. In all regions, the import dependence of indirect energy is greater than the import dependence of direct energy. However, the degree of this disparity varies by region. In East Asia, for instance, the difference is relatively small (17.3% in 2015) because the region has few domestic energy resources and thus relies heavily on energy imports to meet its direct energy demand. Where the difference is greatest is in regions that (i) have abundant domestic energy resources sufficient to meet final direct energy demand, but (ii) rely heavily on imports of goods and services requiring highly globalized supply chains. These regions, which include the Persian Gulf countries and Oceania, may have a false sense of energy security given that their economies are largely but indirectly powered by foreign energy systems. We include a table with regional import dependences in Section 10 of the Supplementary Material.

Tables 1 and 2 present the import and export HHI and number of trade linkages for the ten countries with the greatest embodied energy imports in 2015 (Table 1) and the greatest embodied energy exports in 2015 (Table 2).[25] Collectively, the top ten importers consumed 61% of the world's embodied energy imports while the top ten exporters supplied 54% of the world's embodied energy exports.[26]

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[25] The same information for all countries can be found in the energy security table in the Supplementary Material.

[26] Energy importers (Table 3, Column 2) do not necessarily represent where the primary energy is first used, but where the embodiment of this energy is consumed after undergoing transformations. This is why Russia, the United States, and China are presented as the largest energy exporters; not only are their primary energy resources used directly in a large number of countries, but their goods and services, produced using domestically extracted primary energy, are exported abroad as well.

Table 1. Embodied energy security metrics for top 10 indirect energy importers (2015)

Top 10 importers (energy sinks)									
Importer	**Top 2 import flows**	**HHI (Direct)**	**HHI (Indirect)**	**Linkages (Direct)**	**Linkages (Indirect)**	**Import dep. (Direct)**	**Import dep. (Indirect)**	**% indirect from implicit linkages**	**Embodied sink (EJ)**
USA	Canada (Crude) Venezuela (Crude)	637.94	330.03	399	685	15.59%	39.06%	22.82%	38.86
China	Kazakhstan (Uranium) Saudi Arabia (Crude)	573.08	367.24	318	661	25.36%	40.85%	6.12%	36.05
Japan	Australia (Coal) China (Coal)	876.59	333.93	294	642	67.12%	86.45%	16.79%	16.52
France	Niger (Uranium) Netherlands (Uranium)	1152.32	453.24	370	660	57.18%	68.50%	9.12%	12.89
India	Indonesia (Coal) Saudi Arabia (Crude)	700.19	443.82	312	620	31.51%	55.57%	5.03%	12.26
Germany	Russia (Crude) USA (Uranium)	697.87	293.40	366	663	56.58%	74.27%	17.42%	12.24
UK	Russia (Crude) Canada (Uranium)	907.43	276.98	372	664	66.29%	77.96%	21.37%	11.42
Korea	Australia (Coal) Saudi Arabia (Crude)	629.11	341.52	303	610	52.70%	76.79%	12.32%	7.13
Italy	Russia (Crude) Russia (Natural Gas)	952.30	230.87	304	646	47.30%	70.43%	20.05%	6.10
Russia	Kazakhstan (Uranium) Ukraine (Uranium)	1645.96	1270.63	309	618	23.95%	32.39%	8.37%	6.02

Notes: The first column lists the two largest sources of indirect energy flows into the country. The second and third columns list the Herfindahl-Hirschman Index (HHI) for direct and indirect flows; larger values indicate a more concentrated (less diverse) portfolio. The fourth and fifth columns list the number of energy trade linkages. The sixth and seventh columns list the import dependences. The final column lists indirect energy imports of the country. The eighth column lists the % of indirect energy import that come from energy exporters with which the importer has no direct trade ties. The ninth column lists the total energy sink for that country (EJ).

Table 2. Embodied energy security metrics for top 10 indirect energy exporters (2015).

Top 10 exporters (energy sources)						
Exporter	**Top 2 export flows**	**HHI (Direct)**	**HHI (Indirect)**	**Linkages (Direct)**	**Linkages (Indirect)**	**Embodied source (EJ)**
Russia	China (Crude) USA (Crude)	308.46	215.92	483	913	25.52
USA	Canada (Crude) Germany (Uranium)	514.09	133.86	597	936	20.87
China	USA (Coal) Japan (Coal)	898.75	308.36	607	935	15.95
Canada	USA (Crude) USA (Uranium)	1561.78	990.61	480	931	14.88
Kazakhstan	China (Uranium) Russia (Uranium)	1459.70	1271.87	410	778	14.63
Saudi Arabia	USA (Crude) China (Crude)	1186.49	759.86	271	343	12.88
Australia	Japan (Coal) China (Coal)	1025.74	743.42	478	924	10.99
Venezuela	USA (Crude) China (Crude)	2772.65	1461.80	321	606	8.92
Indonesia	India (Coal) China (Coal)	637.90	513.08	460	776	8.16
Norway	Germany (Natural Gas) UK (Crude)	1199.50	334.32	399	898	6.90

Notes: Columns are the export equivalents to those in Table 2.

For the top ten embodied energy importers, as well as almost all countries (see Sections 9 and 10 in the Supplementary Material), indirect energy portfolios include many more linkages than direct energy portfolios (Tables 1 and 2).[1] This is because primary energy that is embedded in the goods and services demanded by an importer can originate in countries outside of the importer's direct trade network. While producers of primary energy may export this energy to only a handful of countries (i.e. fewer direct linkages), the importers' subsequent use of the primary energy to produce and export a variety of goods and services spreads that primary energy as indirect energy to a larger group of importing countries (i.e. more indirect linkages). For example, as mentioned previously, the United States is one of the three largest importers of indirect energy containing primary energy sourced from Russia (Table 2), a country that exports very little direct energy to the United States. Russia, however, is a major exporter of direct energy to the E.U. and China, and these states use a significant amount of that energy to produce goods and services that are then exported, along with the indirect energy they contain, to the United States (B[1] and D[2] in Figure 10). Thus, while energy systems in Russia and the United States may not interact directly, the systems are still dependent on one another through trade intermediaries.

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[1] Sections 9 and 10 of the Supplementary Material include importer and exporter energy security metrics for 2010 and 2015.

Recall that 23% of the global embodied energy network is comprised of indirect linkages between countries that do not directly trade those energy resources. The importers listed in Table 1 rely on these implicit energy linkages to varying degrees. For instance, 23% of the United States' indirect energy imports originate in countries from which it does not directly import energy resources. On the other hand, only 6% of China's indirect energy imports are based on implicit linkages. Implicit linkages can increase the vulnerability of a national economy to energy shocks beyond their direct trade network. This vulnerability is exacerbated when the nation is unaware of where these risks lie. Of the importers listed in Table 1, the United States, the United Kingdom and Italy are most reliant on implicit energy linkages.

The discrepancy between direct and indirect portfolio diversities is pronounced for Canada and Kazakhstan. Both countries have a much higher HHI and thus smaller, more concentrated consumer network for their direct energy exports than their counterparts. The two countries' indirect energy export portfolios, on the other hand, are much more diverse. This is driven by these countries' uranium exports which, again because of its very high energy density, leads to large uranium indirect energy flows through the global economy. Kazakhstan was the largest uranium exporter in 2015, followed by Canada.[2] Because uranium-based energy can only be used once it has been

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[2] Based on BACI bilateral trade data (Gaulier and Zignago, 2008).

transformed into electricity, direct energy importers will only be those countries that utilize nuclear power generation. However, once this electricity is consumed the uranium energy is embodied in the resulting goods and services. These goods and services have a much wider range of uses, and thus export destinations, explaining why Canada and Kazakhstan have concentrated direct export portfolios but more diverse indirect export portfolios. 79% of Kazakhstan's primary energy exports and 52% of Canada's primary energy exports, when we consider physical energy units (TJ), are in the form of uranium. This means that the majority of the energy exported by these countries can only be used in intermediary countries that use nuclear-generated electricity, indicating that these energy pathways are critical for their energy export security. This is mainly driven by uranium's high energy content, however. These patterns do not inherently translate to economic security. In 2015, uranium exports constituted 1.4% ($2.3 billion) and <1% ($1.7 billion) of Kazakhstan and Canada's GDPs, respectively (Hidalgo and Hausmann, 2009). Uranium places these countries as critical suppliers in the global energy system because it is a low-cost resource with high energy content. However, because the resource can only be used through select intermediaries, these countries' economic dependence on it is limited.

Given that the number of trade linkages is used to solve for the HHI (Equation 3.9), it's reasonable to assume that both would be highly correlated, but for some countries it is not. This is particularly significant in the context of energy security, as it signals a country's dependence on a handful of trading partners out of many. Concentrated portfolios generally mean concentrated risk. Russia, for example, has concentrated direct and indirect energy import portfolios, even though the number of its import linkages is comparable to that of Korea or India. This is largely because of Russia's crucial energy ties with countries that were once part of the Soviet Union. Kazakhstan alone supplied 43% of Russia's embodied energy imports in 2015, with Ukraine supplying an additional 14%. Additionally, Russia acts as an intermediary for the energy flows from these countries to the global energy economy. For example, Russia can transform these primary energy imports into electricity, which it can then export to Europe and Asia.

While export portfolio diversity varies a lot by country, there isn't one form of primary energy that causes exporters to have a more concentrated export portfolio. In fact, Saudi Arabia, the world's largest crude oil exporter, has a relatively low HHI, indicating that its export portfolio is rather diverse.[3] We interpret this to be because of the universal demand for crude oil along with the limited number of countries that export it. Venezuela, another major crude exporter, is an exception to this interpretation. It has a very high export HHI despite having more trade linkages than Saudi Arabia. The reason in this case is because Venezuela sends 60% of its indirect energy exports

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[3] It is relatively low, considering that Saudi Arabia exports primarily one energy commodity (crude oil). In other words, the portfolio of trade partners is diverse even if its portfolio of exports isn't

through just three of its linkages as compared to Saudi Arabia, which sends 43% of its indirect energy exports through its top three linkages. Indonesia, like Venezuela, has more trade linkages than Saudi Arabia. However, unlike Venezuela, Indonesia has a much more balanced HHI. It primarily exports its coal to India, China, and Japan. These countries use this energy to produce goods and services that are then exported to other countries, thereby diversifying the final consumption sink of Indonesian coal exports. This explains its relatively low HHI and high number of trade linkages.

3.4 Conclusion

In this study, we estimate the direct and indirect energy security of countries, sectors, and the global economy and identify areas where they contrast. To do this, we present a new hybrid-unit input-output database, HOMIES, that not only connects the physical flows of energy to non-energy sectors, but also the reverse flow of non-energy goods and services into energy production. This allows us to trace energy flows from the point of primary energy production to final consumption and address the bidirectional feedback between energy and non-energy production processes.

Contrary to many recent studies employing DIO and HIO, we find that the production sources of embodied energy to the global economy are not the countries with the largest energy intensive manufacturing industries (e.g. China) but those countries that initially supply the primary energy consumed for manufacturing (e.g. Russia and

Saudi Arabia). Rather, manufacturing-intensive countries act as intermediary nodes in the flow of embodied energy from production source to final demand sink. Using HOMIES, we identify energy linkages between producers of primary energy and importers of goods and services that only exist through their intermediary nodes. Our results suggest that these linkages account for 23% of the world's embodied energy trade network. The importers in these linkages rely on energy transactions that occur outside of their direct trade networks. This reliance, however, does not inherently make an importer economically vulnerable. For instance, the United States has both abundant energy resources and the capacity to manufacture goods and services domestically, albeit at a much higher cost. It is therefore important to contextualize the implications of implicit energy linkages with each nation's availability of resources and economic status.

Additionally, our results suggest that the import dependence of indirect energy (44%) is much greater than the import dependence of direct energy (23%). It is also much greater than the global trade dependence of primary energy (33%).[4] We also find that indirect energy import dependence varies by primary energy source. Crude oil is the most import dependent form of energy whereas coal is largely sourced domestically before being embodied in goods and services. This is intuitive, as crude oil is demanded

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[4] Trade dependence is calculated for transportable primary energy resources (bioenergy, coal, crude oil, natural gas, uranium) by dividing total trade by total production.

universally but can only be extracted in a few regions, while many countries have coal resources that they largely consume domestically.

Together, these results indicate that the global economy is (i) more dependent on primary energy imports and (ii) a significant share of these imports originate in countries beyond the importer's direct trade network. The latter in particular has significant implications for our understanding of global energy security. Importers that have implicit linkages to foreign primary energy transactions have little policy leverage over the stability of these transactions. They are third party to energy transactions that fuel their supply chains, some of which may be critical to their economies (e.g., automobiles, agriculture). In some instances, these implicit linkages may even be unknown to the importer. On the other hand, primary energy exporters rely on consistent demand for their energy exports. When there is an economic shock in a final demand sector (e.g. food and beverages), this shock reduces demand for intermediate goods and services that go into the sector's supply chain. These intermediate goods and services then reduce their demand for primary energy. Thus, the primary energy exporter's economy is also dependent on implicit energy linkages. This has played out most recently in the wake of the COVID-19 pandemic, which has curbed global demand for Chinese exports. This in turn reduces demand for both primary energy and manufactured inputs in China. This then reduces demand for primary energy in the countries that export manufactured inputs to China. Primary energy producers that are linked to these production processes are therefore impacted by economic shocks that appear to be distant. This lack of awareness increases the vulnerability of importers and exporters to foreign energy shocks. Energy shocks include production disruptions (e.g. Fukushima disaster in Japan), price shocks (e.g. oil price volatility), and transport disruptions (e.g. geopolitical instability in the Strait of Hormuz). While markets may adjust long-term to these shocks, the short- to intermediate-term impacts can be significant. Our results underscore the need to include implicit energy linkages in energy security evaluations.

Finally, metrics of embodied energy security at the country level allow us to identify critical energy import and export intermediaries in the global energy trade network. First, our observation that indirect energy portfolios have more trade linkages than direct energy portfolios suggests that the global economy's dependence on indirect energy is relatively secure. Having more trade linkages benefits the importer of goods and services because the energy requirements of their supply chains are met using a wider variety of energy resources. An upstream energy disruption in one supply chain would not wholly impact the importer's economy. It also benefits the exporter of primary energy because the demand for energy exports are based on a wider-ranging demand for final products. If there is an economic shock that impacts one final demand sector, it would not necessarily impact the entire flow of primary energy out of the country. In other words, a greater number of trade linkages reduces the global economy’s exposure to potential shocks in indirect energy flows. Second, exporters of indirect energy that have a high HHI combined with many linkages tend to be critical sources of primary energy. This primary energy, however, is funneled into the global economy via a handful of importers who use the primary energy in manufacturing exports. For Venezuela, these intermediary trading partners are the United States, China, and India. For Kazakhstan, the main intermediary is Russia. Such intermediary exporters are critical to supplying the global economy with embodied (direct and indirect) energy. Being relatively small in number, however, a disruption in trade through one of these countries could translate into a broader shock to the world trade in energy. In order to fully evaluate the vulnerability of these links in the global energy system, future energy security assessments should be reframed to explicitly include indirect energy flows.

4 The Dependence of the Global Transport Equipment Sector on Maritime Chokepoints: A hybrid-input output approach

4.1 Introduction

Transport equipment manufacturing, which includes the supply chains of passenger vehicles, trucks, trains, and planes, is one of the most valuable sectors in the global economy. In 2015, imports and exports of transport equipment comprised 12% of all international trade by value (Gaulier and Zignago, 2008). And given that global transportation demand has rapidly increased over the last three decades and is expected to grow three-fold by 2050 (OECD, 2019; Rodrigue et al., 2016), the demand for transport equipment (TE) will keep growing as well. In the same way that energy security is defined as the reliable and affordable supply of energy, mobility security can be defined in large part by the reliable and affordable supply of transport equipment (the other part being a combination of fuel supply and transportation infrastructure investment).

The TE supply chain ends with the assembly of TE output and extends backwards through component manufacturing (e.g. engines, seats, tires), to materials manufacturing (e.g. plastics, steel), and finally to raw material extraction (e.g. metals, crude oil). Services are used throughout the supply chain to facilitate the movement of components and materials. The TE supply chain is unique in its complexity. Even at the final assembly stage, it requires inputs from a wide range of industries and countries. In

2015, 22% of the inputs to the global TE supply chain were imported, on average. [5] In terms of inputs to TE manufacturing and transportation services, each country directly interacted with an average of 44 other countries in 2015.[6] Based on these direct country-level transactions, the TE supply chain is the second most interconnected supply chain, following that of electrical and machinery components.

Moving backwards in the supply chain further complicates the network of flows among countries and sectors. For example, TE manufacturing relies heavily on inputs of metal parts. These parts can either be produced domestically (i.e. in the same country where TE manufacturing is taking place) or abroad. The metal parts also require raw material inputs themselves. The outputs of one sector can be inputs to another and the outputs of this latter sector can also be inputs to the former. For example, manufactured steel is used in construction services, while construction services are also required for steel manufacturing. In this way, the supply chain is more a network than a one-directional pipeline.

Vulnerabilities to the TE supply chain are not the same as risks to the TE supply chain. The former describes the areas, both geographic and economic, that have an outsized impact on the functionality of the supply chain if they were disrupted. On the

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[5] TE is the third highest sector in terms of % imported inputs (following mining & quarrying and electrical machinery). TE is the fourth highest sector in terms of % exports over total market (following electrical & machinery, mining & quarrying, and textiles manufacturing).

[6] Based on author's calculations of data from the Eora input-output database (Lenzen et al., 2013).

supply side, vulnerabilities impact the ability of a supply chain to manufacture a product or render a service. On the demand side, vulnerabilities impact the delivery of these outputs. Risks, on the other hand, describe the supply chain hazards themselves. They include geopolitical hazards, social unrest, and environmental degradation. Most recently, the outbreak of COVID-19 caused factory shutdowns in China that led to reduced production of intermediate TE components. Because the supply chain is particularly vulnerable to disruptions in these products, this shock quickly propagated throughout the global TE supply chain (Sorensen and Telang, 2020). These shocks were significant even before COVID-19 became a global pandemic, largely due to the time-sensitive nature of the TE supply chain. Most TE manufacturers have storage times of 1-2 months (Donnan, 2020).

In addition to large-scale systemic shocks (like a global pandemic), smaller operational and logistical disruptions can propagate throughout the TE supply chain. One area of the supply chain that is particularly vulnerable to disruptions is shipping. Over 90% of international trade is conducted via maritime routes (UNCTAD, 2018). Disruptions to maritime trade routes therefore pose a risk for the TE supply chain because they could not only impact the delivery of TE, but also all of the component inputs to TE manufacturing. Maritime chokepoints, narrow waterways that are highly transited by trading vessels, have increasingly become hotspots for geopolitical, environmental, and economic volatility. Existing studies have examined risks to chokepoints in the context of global food security (Bailey and Wellesley, 2017; Wellesley et al., 2017) and energy security (Komiss and Huntzinger, 2011; Rodrigue, 2004b; Shepard and Pratson, 2020a). However, no study to date has evaluated the dependence of the TE supply chain on maritime chokepoints and the risks that this dependence can cause.

The objective of this study is to understand the dependence of the TE supply chain on transit through maritime chokepoints. Dependence is best understood in the context of vulnerability, rather than risk. A higher chokepoint dependence indicates that the supply chain is more vulnerable to chokepoint disruptions. From a demand-side perspective, such a disruption could stymie the growing demand for new TE products in rapidly developing countries. However, the biggest impacts of a disruption stem from the fact that the TE supply chain branches into many other industrial sectors. A disruption in the flow of TE products can cause secondary shocks in the demand for intermediary products, such as electrical machinery and steel. This demand shock could subsequently cause employment shocks, which have economy-wide implications. Because the TE supply chain is so interconnected, supply chain risks are in fact risks to the global economy.

The global TE market is driven by its major exporters and importers. The ten largest TE exporters in 2015 produced 74% of global TE exports. The ten largest TE importers consumed 57% of global TE imports. A chokepoint disruption would most heavily impact the global TE market through these major players. This study highlights the largest exporters of TE manufacturing to understand the chokepoint dependence of TE exports overall. To understand the chokepoint dependencies of major consumers, it highlights China and the United States only. The United States is highlighted because it is historically the largest consumer of TE, both domestically-produced and imported. China, on the other hand, has emerged as a major consumer and its growth in consumption has yet to plateau as of 2015. The U.S. and China therefore represent two extremes that other TE consumers fall between. These countries are dependent on chokepoints to meet their household demand for TE; however, the drivers for each country's dependence are unique.

4.2 Background

4.2.1 Existing literature on chokepoint dependence

This study examines the TE supply chain through the lens of chokepoint dependence. This is similar to the ways in which past studies have examined oil and gas supply chains. In fact, the vast majority of the existing literature on chokepoint risks have focused on the impacts of chokepoint disruptions to the global supply of crude oil. There are two reasons that chokepoint-related studies have focused on energy security. The first is that crude oil is universally demanded, but can only be produced in select regions. Unlike other primary energy resources, like coal, most of the crude oil that is produced is ultimately exported. The market for crude oil therefore relies heavily on international trade. Secondly, crude oil shipments rely on tanker traffic via maritime routes. One of the key energy-producing regions in the world surrounds the Persian Gulf. Fuel exports from the region must transit the Strait of Hormuz first before they can be transported to other regions. Transit through the Strait of Hormuz is necessary, but the chokepoint is also vulnerable to geopolitical instability.

TE supply chains, unlike oil supply chains, do not *necessitate* chokepoint transit. Most countries that export the component inputs into TE manufacturing could use alternative maritime routes to ship their products. For example, if there were a disruption in the South China Sea, Chinese exports of electrical machinery could bypass transit through the chokepoint by moving to the north first, rather than to the south. While this adds to shipping costs (e.g. through insurance costs), it does not prohibit China from participating in the TE supply chain.

Therefore, the dynamics of how chokepoint disruptions influence the oil supply chain are different from those that influence the TE supply chain. The first dynamic is how export shocks from chokepoint disruptions propagate upstream in the supply chain. When a geopolitical incident in the Strait of Hormuz induces a shock to oil exports, oil-producing countries are directly impacted. However, because crude oil represents the most upstream node in the oil supply chain, this shock does not propagate upstream. The chokepoint disruption influences a node with a low backward linkage. Forward linkages represent sectors whose outputs (i.e. supply) are required for nodes downstream in the supply chain. Backward linkages represent sectors whose inputs (i.e. demand) impacts upstream nodes in the supply chain (Dietzenbacher, 2002). Crude oil extracting requires fewer inputs relative to TE manufacturing. The direct impacts of chokepoint disruptions to exporters are therefore limited to the oil producing countries themselves. In the TE supply chain, the TE manufacturing country has a high backward linkage. This is because TE manufacturing requires many inputs (i.e. has high demand for upstream sectors) and produces inputs to other sectors (i.e. transportation). Therefore, a chokepoint disruption would directly impact the TE-exporting countries and this shock would quickly propagate upstream in the supply chain.

The second dynamic relates to how chokepoint disruptions can propagate downstream in the supply chain. Crude oil is a critical input for many global supply chains. This means that when disruptions stymie crude oil exports, they can effectively shut down supply chains. Crude oil therefore has a high forward linkage. TE output, on the other hand, is not necessary for most supply chains to continue operations. Part of this is due to the longer turnover of TE; light-duty autos have lifetimes averaging 16.9 years while aircrafts have lifetimes exceeding 27.5 years (Bureau of Transportation Statistics, 2019; Davis et al., 2012). This means that countries can rely on the existing stock of TE for quite a while before requiring newly manufactured inputs. A chokepoint disruption may therefore not have as large an impact on countries that have robust transportation systems. However, for developing countries that are relying on an inflow of TE to establish their transportation systems, such a disruption can have far more significant implications.

4.2.2 Studies on transport equipment supply chains

Quantitative analyses on the TE supply chain largely fall into two groups, categorized by research objectives. The first group of studies aims to optimize logistics in an effort to increase operational efficiencies (Bhaskaran, 1998; Díaz-Madroñero et al., 2014). Many of these studies rely on firm-level data to explore the local and regional dynamics of the TE (mostly automobile) supply chain (Doran et al., 2007). The second group aims to understand the emissions footprint of the TE supply chain. A particularly important analysis in this area was Timmer et al. (2015), which used the automotive industry as a case study for illustrating the World Input-Output Database (WIOD), one of the key global supply chain databases. In their study, the authors illustrate the simultaneous regionalization and globalization of activities in the supply chain (Timmer et al., 2015). Kagawa et al. (2013) and Tokito (2018) used a combination of clustering analysis and structural decomposition analysis (SDA) to identify emissions hotspots in the TE supply chain (Kagawa et al., 2013; Tokito, 2018).

The methods used in this analysis stem from the literature in this second group, but focus more on vulnerabilities in the supply chain. One of the main methods used in this kind of analysis is input-output analysis (IOA). IOA has been used extensively in the environmental and economic systems literature to understand the direct and embodied consumption patterns of national, regional, and global economies (Bortolamedi, 2015; Chen and Chen, 2011; Kitzes, 2013; Xie et al., 2018). Studies that employ IOA first represent an economy as a system (here, a matrix) of financial inputs and outputs, wherein rows represent sectors' monetary inputs required to produce a monetary unit of output from a column sector. This matrix represents the direct interconnections among sectors, and is called the technical coefficients matrix. After building the technical coefficients matrix, researchers can apply a Leontief inversion to estimate the total interconnections matrix (also called a Leontief matrix) which includes both direct and embodied financial requirements.

IOA has also been widely used in supply chain analyses to map out the supply chains for specific products, such as leather (Albino et al., 2002) and furniture (Ocampo et al., 2016), as well as for key regions like the European Union (Kucukvar and Samadi, 2015; Mair et al., 2018) and China (Xing et al., 2011). IOA for supply chain assessments are typically conducted at the macro level, though several studies exist that explore IOA applications to firm-level business decisions (Aviso et al., 2018; Lin and Polenske, 1998).

More recently, methodological developments in IOA have allowed for the representation of perturbations through a supply chain. This development, called inoperability input-output modeling (IIM), estimates the supply chain impacts of exogenous shocks (Wei et al., 2010). Impacts from short-term shocks are estimated by leveraging the interdependencies among industries in an IOA, combined with an additional vector (the "inoperability vector") representing the ratio of realized productivity over business-as-usual (BAU) productivity (Anderson et al., 2007). IIM has been applied to simulate the effect of short term shocks, including terrorism activity (Santos and Haimes, 2004) and influenza (Santos et al., 2013) on regional supply chains.

These studies present useful insights to policymakers on the risks of short-term shocks. However, they apply a uniform shock to an entire IO system by applying the inoperability vector to an unchanged technical coefficients matrix. Because of this, they do not model shocks that impact specific subsets of the economic system. For example, say China and the United States' industrial activities are represented in a two-region IO matrix. The technical coefficients matrix shows that $0.60 of U.S.-produced steel input is required per $1 of Chinese machinery output (note: these numbers are hypothetical). An IIM framework assumes that all $0.60 of input is impacted uniformly by a shock. However, perhaps only 20% of the $0.60 input is in the location of the shock. This would change the effects of the shock on the supply chain. In other words, while IIM is useful in large-scale, short-term shocks, they do not have the geographic specificity needed to estimate the impacts of smaller-scale, regional shocks that impact transactions *between* regions, including chokepoint disruptions. This study builds on the existing literature by adding this geographic specificity to IOA to map out the vulnerability of the TE supply chain to maritime chokepoint disruptions. This is a required first step in simulating how such a disruption might propagate through the supply chain, and one that hasn't been taken to date.

4.3 Methods

4.3.1 Measuring chokepoint dependence

The objectives of this analysis can be summarized by two questions. First, how dependent are the major TE exporters on transit through maritime chokepoints? Dependence here can be measured in two ways: (i) through the inputs to TE manufacturing and (ii) through the exports of TE output. The second question is, how dependent are major TE importers on transit through maritime chokepoints? Similarly, to the first question, this can be answered in two ways: (i) through the direct imports of TE and (ii) through the inputs required to produce the TE that is imported. A visual representation of both of these mechanisms can be found in the Supplementary Material.

These two types of flows comprise *direct* chokepoint dependence. In this analysis, direct chokepoint dependence is defined as the reliance on chokepoint transit between countries that are directly trading goods and services. This is illustrated in connections a1 and b1 in Figure 15, below. On the other hand, indirect chokepoint dependence would impact the countries further along in the supply chain. This dependence exists due to the dependence of an intermediary node in the supply chain.

This is illustrated in connection a2 in Figure 15. Because the TE sector requires many different types of inputs from many different countries, this kind of chokepoint dependence would add up quickly.

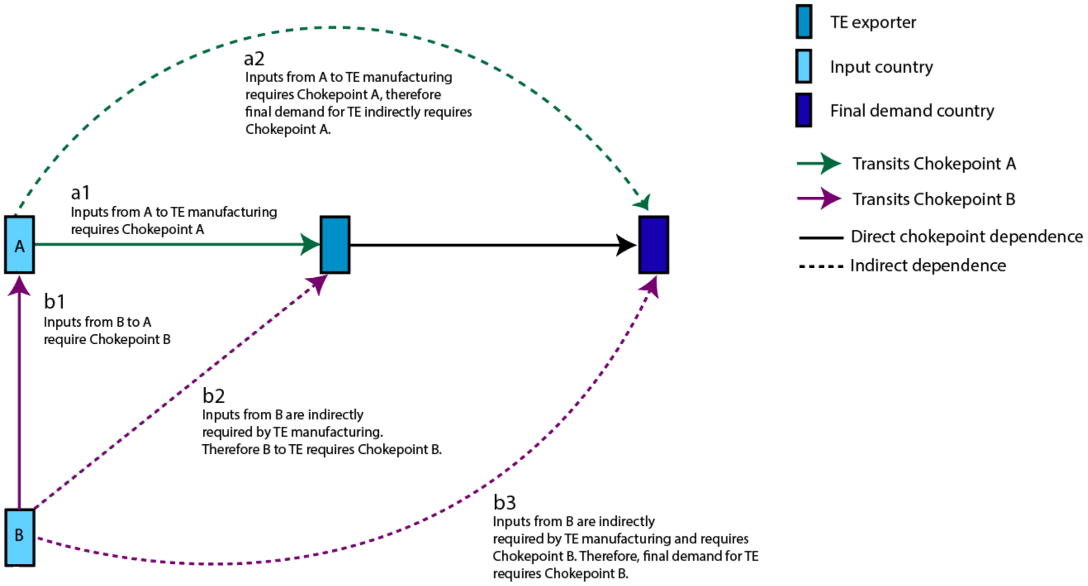

Figure 15. Schematic of direct and indirect chokepoint dependence. Connections a1 and a2 illustrate how the direct chokepoint dependence between an input to TE manufacturing and the TE manufacturing sector leads to indirect dependence on that chokepoint by the final demand. Connections b1 and b2 illustrate how the TE manufacturing sector can be indirectly dependent on a chokepoint if one of its inputs requires that chokepoint to receive an input itself. This dependence propagates downstream to the final demand, as illustrated in connection b3.

The boundaries of this analysis can be expanded even further. The direct and indirect chokepoint dependencies describe what happens at the final stages of a supply chain; either getting the final inputs to the TE sector or delivering TE output to meet final demand. However, all of the steps leading up to this final stage can also depend on chokepoints. This analysis builds on Shepard and Pratson (2020)'s distinction between direct and indirect energy use. If TE manufacturing requires an input whose own inputs require chokepoint transit, the TE manufacturing sector is indirectly dependent on that chokepoint. This is illustrated in connection b2 of Figure 15. This dependence extends to the final demand for TE as well, as illustrated in connection b3. Because the TE supply chain is so globalized and complex, disruptions to chokepoint transit further up in the supply chain can have significant implications for meeting final demand downstream. The sum of all of these dependences defines total chokepoint dependence.

4.3.2 HOMIES

This study relies on IOA to represent economic systems. This is because the goal is to estimate both the direct and embodied trade flows into the manufacturing of TE. In an IOA, economies are represented as matrices, in which each row and column corresponds to a sector. The values in the matrix represent the inputs, or the intermediate transaction, from a row sector to a column sector. The total output of a sector is the sum of its intermediate transactions and the final demand for the sectors' outputs.

$$x_j = Z_j + f_j$$

[Equation 4.1]

Where x is the total economic output for sector j, Z_j is the sum of the sector's intermediate inputs, and f_j is the sector's final demand. x_j is a single value, whereas x is a vector that contains all sectors' economic outputs. The per-unit requirements of the sectors' activities are calculated by dividing the intermediate transactions matrix by total output.

$$A = Z\hat{x}^{-1}$$

[Equation 4.2]

Where $\hat{x}^{-1}$ is a diagonalized matrix of the x vector, inverted. It has the same dimensions as the intermediate transactions matrix Z. A is therefore a matrix of per-unit inputs into each represented sector. This matrix is also called the direct requirements matrix or the technical coefficients matrix. Finally, one can calculate the *total* requirements for producing sectoral output by inverting the technical coefficients matrix.

$$L = (I - A)^{-1}$$

[Equation 4.3]

In this formula, L represents all of the direct and embodied inputs that are required by each sector to produce one unit of output. This matrix is also called the

Leontief matrix named after Wassily Leontief, who developed this methodology and received the Nobel Prize in Economics for his contributions. To assess the total economic activity, one simply multiplied the L matrix by the vector for final demand (f).

$$x = Lf = \left[l_{ijqr}\right]_{IQ\times JR}\left[f_{jr}\right]_{JR\times 1}$$

[Equation 4.4]

L is a matrix in which each cell l_{ijqr} represents the total requirements from sector q in country i to produce a unit of output in sector r in country j. L is a square matrix and the number of rows (or columns) is equal to the product of the number of countries (I or J) and the number of sectors represented (Q or R). f is a vector in which each value represents the final demand for sector r in country j. f has units equal to the number of rows (columns) in L. The dimensions of the L matrix are equal to the dimensions of Z and A. The total economic output, x, will have dimensions equal to f, except in this case the values represent the input required from sector q in country i to meet final demand.

When the IOA framework is applied to more than one economy, a multi-regional input-output analysis (MRIO) is used. In MRIO, rows and columns are added for each sector in each region. Several MRIO databases have been developed to represent the global economy, including the World Input-Output Database (WIOD), EXIOBASE, and

Eora (Lenzen et al., 2013; Moran and Wood, 2014; Stadler et al., 2018; Timmer et al., 2015).

Since its development, IOA methodologies have been further developed to address environmental impacts of economic activity. These methods fall under the category of environmentally-extended input-output analysis (EEIOA). Studies that have employed EEIOA have evaluated the carbon footprints of major economies (Bortolamedi, 2015; Kaltenegger et al., 2017; Kan et al., 2019), sectors (Bekhet and Abdullah, 2010; Hong et al., 2016; Ozkan et al., 2004; Pietroforte and Gregori, 2003; Tang et al., 2012), and regions (Cicas et al., 2007; Su and Ang, 2014). EEIOA also has the capacity to estimate the material flows within an economic system, including copper (Liao et al., 2019; Soulier et al., 2018) and iron (Konijn et al., 1997; Nakajima et al., 2013). These studies typically use an EEIOA approach called direct input-output analysis (DIO). In DIO, the conventional IOA is used to first estimate the direct and embodied monetary flows among sectors (i.e. the L matrix) and then multiply these transactions by their corresponding emissions factors *ex-post*. This yields a new matrix, L_E, of the per-unit emissions associated with the given sector's activity. By multiplying L_E by the final demand vector (f), one can estimate the total emissions footprint of the economic system (x_E). Another approach to solving EEIOA is to use a hybrid input-output approach (HIO), in which the environmental variables of interest (e.g. carbon dioxide, energy) are included as additional rows in columns in the underlying transactions matrix (Z) and final demand vector (f). These objects therefore have mixed units representing in the case of energy: energy required for monetary outputs (TJ/USD), energy required for energy production (TJ/TJ), monetary inputs required for monetary outputs (USD/USD), and monetary inputs required for energy production (USD/TJ). HIO is favored over DIO when data are available. This is because HIO, unlike DIO, is able to: (1) capture energy resources from where they are first produced, rather than where they are first consumed, (2) follow the transformation of energy from primary energy to secondary energy, and (3) relax assumptions in DIO, such as the assumption that energy costs are held constant across sectors. The primary drawback to HIO is that it is extremely data-intensive.

This study uses a new database called the Hybridized Option for Modeling Input-Output Energy Systems (HOMIES). HOMIES is based on the Eora database, but applies an HIO framework to solve for international energy flows. It follows the monetary and energy flows among 26 non-energy sectors, 13 energy types, and 136 countries over 20 years (1995-2015). This long temporal dimension provides insight on major economic and energy transitions, such as the dissolution of the Soviet Union, China’s emergence into the global economy, and the rise in unconventional oil and gas exploration in North America (Shepard and Pratson, 2020b). This study employs HOMIES because this analysis similarly captures the entire scope of the transport equipment supply chain.

4.3.3 Shortest routes algorithm

The first part of this analysis is to assign an indicator to each country-country pair if its corresponding trade flows require transit through a maritime chokepoint. Shipping is generally assumed to be conducted along the shortest sea route between two countries. While alternative routes exist that can avoid chokepoints, we assume that the shortest route would be taken given that longer routes would require additional costs associated with fuel, insurance, labor, and capital. For each country, a set of ports is selected that represent major throughputs for imports and exports. For most countries, this set includes only one port. For countries with coasts along more than one body of water, the set may include up to three ports. The United States, for instance, has a set that includes ports in California, New York, and the Gulf Coast. Each port is treated as a proxy for other ports along the coast; for the vast majority of countries, adding a port along the same coast does not change the shortest shipping route. The shortest path between each port-port pair is calculated within each country-country pair. These paths are constructed by connecting equidistant nodes on a global map. From these paths, shortest routes are identified in the country-country pair.

After running this process, 6,869 unique paths are left among all countries. An indicator is assigned to a country-country pair if its shortest path requires transit through a key maritime chokepoint. The chokepoints included in this analysis are as follows: the Bab el Mandeb Strait, Bosporos Strait, Denmark Strait, East China Sea, English Channel, Gibraltar Strait, Makassar Strait, Malacca Strait, Ombai Strait, Panama Canal, South China Sea, Strait of Hormuz, and the Suez Canal. Figure 16, below, illustrates the shortest routes among countries in our analysis. It is constructed as a kind of heat map from yellow to red; dark red lines signify that a path is used in more routes.

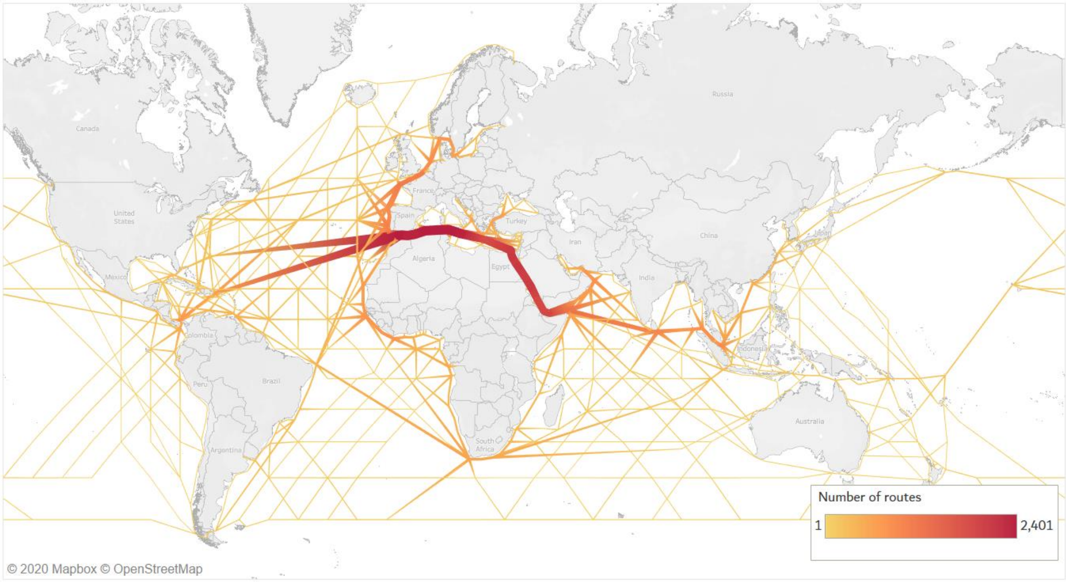

Figure 16. Shortest routes among countries in this analysis. There is a total of 6,869 routes. Yellow lines represent nodes (or paths) through which only one country-country route transits. Red lines represent heavily transited nodes (or paths).

This figure illustrates that most of the shortest routes that are used in bilateral trade must transit the Strait of Hormuz, Red Sea, Suez Canal, and the Strait of Gibraltar. This is because most of the routes between Asia (i.e. East Asia and South Asia) and the West (i.e. North America and Western Europe) will cut through waterways in North Africa rather than circumventing the African continent via the Cape of Good Hope in the south. Note that these shortest routes are solely based on geography; in other words, they do not include other compounding factors like currents, geopolitical conditions, or tariffs. We also assume that all bilateral trade between two countries will utilize the shortest route between them and do not consider cases in which a vessel may use another route because it makes multiple stops among a number of bilateral trade partners. For example, an oil tanker may move crude oil from Saudi Arabia to India on its way to delivering crude oil to Australia and Japan. Our shortest route, while providing a proxy for *averaged* shipping paths, does not have this level of specificity. While approximate, the maritime chokepoints associated with the shortest routes would be transited by most (if not all) paths between the corresponding trading pair.

4.3.4 Chokepoint extensions for HOMIES

In order to understand trade dynamics through key maritime chokepoints data on shortest routes are linked to chokepoint transits to the HOMIES database. We call this project the HOMIES-Chokepoint extension, or HOMIES-CE. HOMIES-CE separates out the bilateral transactions that, based on the shortest route algorithm explained above, must transit a chokepoint. Mathematically, this amounts to multiplying the HOMIES matrix of hybrid-unit transactions to a matrix that represents chokepoint transits:

$$Z^c = ZC = \left[z_{ijqr}\right]_{IQ\times JR}\left[c_{ijqr}\right]_{JR\times IQ}$$

[Equation 4.5]

Z represents the matrix of transactions from Equation 4.2, in which each cell (z_{ijqr}) represents the transaction between sector q in country i and sector r in country j. As in Equation 4.4, this matrix is a square matrix with dimensions equal to the product of the number of countries and the number of sectors included in the analysis. C is another square matrix with the same dimensions as Z. c_{ijqr} is set equal to one if the shortest route between countries i and j requires transit through the given chokepoint. Otherwise c_{ijqr} is set to zero. Because the shortest route change by trading pair, but not by sectoral pair, c_{ijqr} will be the same across all q and r. In other words, $c_{ijqr} = c_{ij}$. The resulting matrix, Z^C, will be set to z_{ijqr} if the transaction requires chokepoint transit and zero otherwise. Each chokepoint of interest is assigned a chokepoint matrix and there exists a HOMIES matrix for each of the 20 years represented in this analysis (1995-2015). This process runs 260 times for each year-chokepoint combination.

The matrix c represents the transactions that directly rely on chokepoint transit based on the shortest path algorithm. However, a country's dependence on a chokepoint is based not only on its direct imports and exports, but also on its indirect trade patterns. For instance, say Japan imports \$100 of agricultural output from India and that the shortest route between the two countries must transit the Malacca Strait. This means that

$100 of agricultural output must transit the Malacca Strait. However, India imports crude oil from Saudi Arabia and some of this energy is used in the Indian agricultural sector. The shortest route between Saudi Arabia and India requires transit through the Strait of Hormuz. In this instance, some of the Saudi Arabian crude oil will be embodied in the agricultural output that is exported to Japan. Therefore, Japan's imports of Indian agricultural products are not only dependent on the Malacca Strait, but are partially dependent on the Strait of Hormuz as well. HOMIES-CE captures these indirect chokepoint dependences in addition to the direct dependences represented by Z^c.

To capture both of these chokepoint dependencies, a methodological development is made to large-scale MRIO analyses. First, the matrix Z^c is used to calculate the share of the total output from each country and sector that transits the chokepoint. The resulting matrix is the B matrix:

$$B^C = Z^C \hat{x}^{-1}$$

[Equation 4.6]

Where the B matrix for a given chokepoint C is the product of the chokepoint transactions matrix Z^c and the diagonalized inverse of total economic output. Note that Equation 4.6 is analogous to Equation 4.2, which calculates the technical coefficients (or direct requirements) matrix. From B, the *weights* for chokepoint dependence are calculated by taking the sum across all inputs to each country-sector pair in B. The resulting vector will have dimensions of $1 \times JR$, because it is the column sum of a matrix with dimensions equal to $IQ \times JR$. This vector is called the weights vector (w). The element-wise (Hadamard) product of the chokepoints matrix C and w is then calculated to build a chokepoint-weight matrix (V).

$$V = \left[v_{ijqr}\right]_{IQ\times JR} = C \circ \widehat{w} = \left[c_{ijqr}\right]_{IQ\times JR} \circ \left[w_{ijqr}\right]_{JR\times IQ}$$

[Equation 4.7]

Here, $\widehat{w}$ is the diagonalized weights vector (w). Where c_{ijqr} is equal to one (i.e. direct dependence on chokepoint), v_{ijqr} will also equal one. Where c_{ijqr} is equal to zero, v_{ijqr} will equal the total weight for the given transaction (w_{ijqr}). Recall that $c_{ijqr} = c_{ij}$; chokepoint dependence does not change by sector but by country because the shortest routes are calculate for each country-country pair. However, w_{ijqr} may change by sector because the countries that provide inputs to one sector are not the same as those that provide input to another. In our example above, the inputs to the agricultural sector in India may require crude oil inputs from Saudi Arabia while inputs to the textiles manufacturing sector do not. w_{ijqr} would reflect the heterogeneities in sectoral inputs. This type of heterogeneity in direct chokepoint dependences does not need to be addressed because it is assumed that all trade between two countries are conducted via the same maritime path (i.e. the shortest route). Using the chokepoint-weight matrix, a matrix of chokepoint-weighted transactions is constructed by calculating the Hadamard product of the original transactions matrix (Z) and the chokepoint-weight matrix (V).

$$Z^V = \left[z_{ijqr}^V\right]_{IQ \times JR} = Z \circ V$$

[Equation 4.8]

Finally, the resulting matrix (Z^V) is treated as though it were the original transactions matrix (Z) in a conventional IO analysis. Its corresponding technical coefficients matrix (A^V) is constructed as follows:

$$A^V = Z^V \hat{x}^{-1}$$

[Equation 4.9]

Where the weighted transactions matrix is divided by total output to get the requirements per unit output (i.e. 1 USD) that relies on transit through the given chokepoint. Finally, the total amount that relies on a chokepoint is calculated by estimating the Leontief inverse for A^V and multiplying it by final demand:

$$x^C = L^V f = (I - A^V)^{-1} f$$

[Equation 4.10]

The resulting matrix L^V and vector x^C provide two valuable metrics for understanding the dependence of an economy on the given chokepoint. L^V provides a per-unit requirement that requires chokepoint transit while x^C provides the total value that requires chokepoint transit. These metrics serve different purposes. The per-unit metric (L^V) provides insight on the extent to which the transport equipment's supply chains are globalized. Globalization is assessed by simply evaluating the number of countries that provide direct and indirect inputs to the transport sector in a given country. By including the indirect inputs, the countries that provide "inputs to inputs" are incorporated, e.g. Chile would be included in Japan's transport equipment supply chain because Chile exports copper to China, which uses this copper to build machinery that is used to manufacture transport equipment in Japan. This expands the boundaries of the transport equipment supply chain. The total metric (x^C), on the other hand, evaluates the necessity of chokepoint transit to meet final demand. It therefore gives more insight on how economic growth (as measured by household consumption, or final demand) has impacted the inputs to meet that demand. As final demand increases, the amount of transport equipment transiting a chokepoint is likely to increase.

An increase in the value of transport equipment transiting a chokepoint does not necessarily lead to a corresponding increase in chokepoint *dependence.* Dependence is based on whether total transportation equipment output to meet final demand also increases. If the increase in total output is less than the increase in output transiting the chokepoint, dependence will increase. Chokepoint *dependence* is evaluated by calculating (i) the fraction of total per-unit requirements (L) that L^V comprises, and (ii) the fraction of total economic output (x) that x^C comprises. These fractions are based on the Hadamard product of the chokepoint-based object and the inverse of the total object.

$$s_x = x^C \circ x^{-1}$$

[Equation 4.11]

$$s_L = L^V \circ L^{-1}$$

[Equation 4.12]

The resulting matrices are subsetted to the values corresponding to transport equipment. s_x represents the dependence on the given chokepoint to *supply* transport equipment. This is particularly useful when evaluating the major exporters (i.e. producers) of transport equipment. s_L represents the dependence on a given chokepoint to meet final demand for transport equipment. This metric is more useful for understanding the major importers (i.e. consumers) of transport equipment.

4.4 Results

4.4.1 Major players in the TE market

Understanding the nature of chokepoint dependencies requires context. Major exporters of TE, including Germany, the United States, Japan, and France, rely on the sector for a large share of their GDPs. Table 3 presents the ten largest TE exporters in 2015.

Table 3. Top ten exporters of transport equipment (2015)

	Exporter	Transport equipment exports ($1000)	Share of all exports	Share of 2015 GDP
1	Germany	295142692.6	16.76%	7.98%
2	USA	219258627.4	12.45%	1.32%
3	Japan	165040406.8	9.37%	2.76%
4	France	113517932.5	6.45%	4.09%
5	South Korea	107181420.1	6.09%	8.45%
6	Mexico	100574379	5.71%	8.31%
7	China	95689991.68	5.44%	1.07%
8	Canada	74629542.44	4.24%	4.15%
9	UK	68202168.14	3.87%	2.54%
10	Spain	55961926.42	3.18%	3.96%

Notes: Transport equipment values are given in thousands of USD (adjusted for inflation). The third column gives the share of TE exports over the country's total exports. The fourth column gives the share of TE exports over the country's 2015 GDP.

Some countries rely on TE equipment, even if their exports do not comprise a large share of the global market for TE. Slovakia, for example, exported $20 billion in TE in 2015 (making it the 19th largest exporter in the world) but these exports comprised 20.1% of its GDP that year. Other countries that are reliant on TE exports are Hungary

(12.8% of 2015 GDP) and Slovenia (8.5% of 2015 GDP). Three of the top ten exporters are also dependent on their TE sectors for their GDPs: South Korea (8.4% of 2015 GDP), Mexico (8.3% of 2015 GDP), and Germany (8% of 2015 GDP).

The list of major TE importers overlaps with the list of major TE exporters. The United States, Germany, the United Kingdom, China, and France are the five largest importers by total value of TE imports.

Table 4. Top ten importers of transport equipment (2015).

Top 10 by import value ($1000)			Top 10 by share of total imports in 2015		
Importer	**TE imports ($1000)**	**Share of all imports**	**Importer**	**TE imports ($1000)**	**Share of all imports**
USA	332280666.1	15.39%	Malta	6238503.317	50.23%
Germany	129924462	13.13%	Panama	9116758.535	32.68%
UK	101167446.8	16.67%	Niger	705436.4369	29.11%
China	97005165.07	7.63%	Qatar	8351511.782	24.08%
France	85702009.52	15.37%	Sri Lanka	4764688.068	22.71%
Canada	77745712.62	19.19%	Bahrain	2844668.168	22.01%
Belgium	45550100.1	12.05%	Norway	17685187.89	21.85%
Mexico	42454621.01	11.25%	Brunei	841374.004	21.65%
Spain	42121286.57	13.92%	Canada	77745712.62	19.19%
Italy	41581344.21	10.27%	New Zealand	6684428.732	18.70%

Notes: Transport equipment values are given in thousands of USD (adjusted for inflation). The left three columns are the top ten importers by import value (in thousands USD). The right three columns represent the top ten importers by what % of the country's total imports are comprised by TE imports.

Some countries import less in terms of total value, but more in terms of the share of total imports. For example, Qatar imported $8.3 billion of TE in 2015 (making it the 41st largest importer in the world that year), which made up 24% of its total imports. In general, TE comprises a significant share of total imports in the ten largest importers by value as well. China is a bit of an outlier as of 2015, primarily because it is still in the midst of rapid growth in its transportation demand.

4.4.2 Transport equipment producers

4.4.2.1 Exports of transport equipment

In this section, the chokepoint dependence of major exporters s_x (defined in Section 4.3.3) is estimated for every combination of key chokepoints and the eight largest TE exporters in each year between 1995-2015. This first metric only estimates $s_x$based on the *outflow* of TE from these eight countries. In other words, this metric does not yet address inputs into TE manufacturing activity.

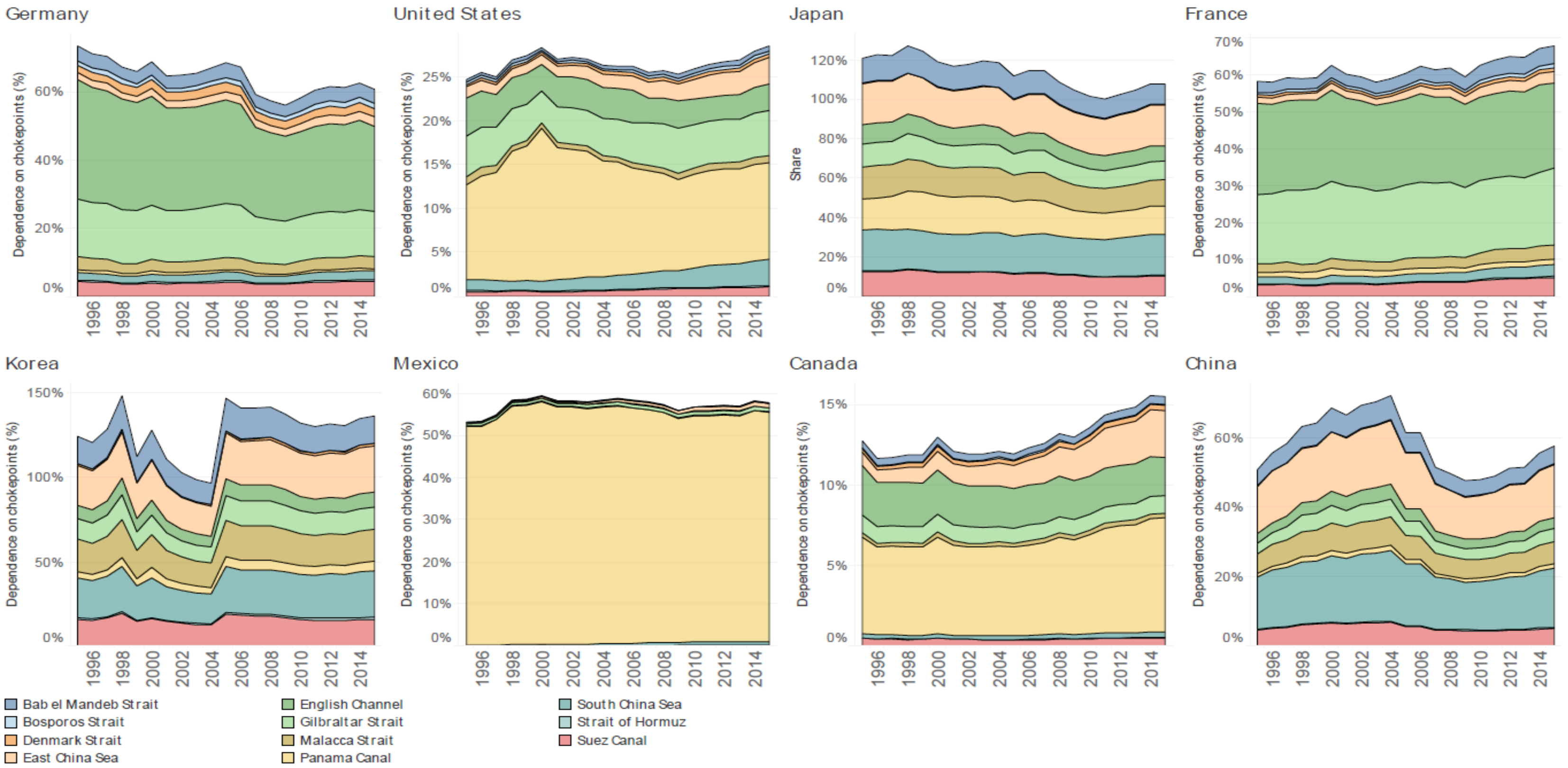

Figure 17. Chokepoint dependence as a percent of total transport equipment (TE) exports. Each line is colored by chokepoint. The countries that are presented represent the largest TE exporters in 2015. Canada and the United States, which have low dependencies by chokepoint, are the least reliant on chokepoint transit overall. On the other hand, Germany and Korea are the most reliance on chokepoint transit overall. Mexico is an outlier in that it is heavily reliant on the Panama Canal but does not rely on other chokepoints as much. The mechanisms behind Mexico and Korea's dependencies are explored in the main text. Note that while these values are shown as a stacked area graph, chokepoint dependence is not additive (i.e. 70% dependence on the Panama Canal and 30% dependence on the Malacca Strait does not mean that the country is 100% chokepoint dependent). This would be double counting the dependencies.

On average, the major TE exporters are 23% dependent on their most transited chokepoint. Overall chokepoint dependence (i.e. the dependence of exports to at least one chokepoint) is on average 5.8%. Our results indicate that Mexico is, by far, the most dependent on a single chokepoint (the Panama Canal) for its TE exports.[1] This value, ranging from 52% in 1995 to 58% in 2014, remains consistent throughout the time period of our analysis. Japan's TE exports also relied on the Panama Canal, particularly between 2000 and 2008. However, its exports through the Panama Canal declined substantially during the Great Recession (2009) due to reductions in the final demand for TE in the United States and Canada. Even during the economic recovery of 2010-2015, Japan's dependence on the Panama Canal did not return to previous levels. This is largely driven by a shift in the United States' household demand for imported TE, which has yet to fully recover as of 2015 and has shifted toward domestically-produced output.[2] Note that while the shortest path algorithm does not directly link Japan to the United States through the Panama Canal, Japan still relied on the Panama Canal because products that have Japanese TE embodied in them were ultimately imported by the United States via an intermediary country. The reduction in Japan's dependence on the

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[1] This dependence does not include the direct trade between Mexico and the United States. The two countries may be linked, however, if Mexico exports to an intermediary country that then re-exports to the United States.

[2] U.S. household demand for Japanese transport equipment was $28.1B in 2008, $21.3B in 2009, and $25.4B in 2015. On the other hand, U.S. household demand for domestically produced transport equipment was $138.6B in 2008, $133.4B in 2009, and $140.8B in 2015.

Panama Canal is counteracted by an increased dependence on the South China Sea. These results highlight that large, exogenous, economic shocks like recessions do not only contract the global economy, but can also have lasting effects on the *composition* of globalized supply chains. These long-term impacts change the risks that nations face in shipping their exports abroad.

Korea, in 2005, experienced a sharp increase in its dependence on chokepoints for TE exports. This increase can be observed across chokepoints. However, there is no corresponding increase in the total value of TE exports during this time. To explore the mechanisms driving this anomaly, we look at the household demand for Korean TE across countries represented in HOMIES. Results suggest that in 2005, Korean household demand for domestically-produced TE increased by 16%. Meanwhile, foreign household demand for Korean TE decreased unilaterally.[3] This means that the denominator in the chokepoint dependence metric s_x decreased significantly between 2004 and 2005. Because the countries that necessitate chokepoint transit observed a smaller reduction in household demand for imports than those that do not require chokepoint transit, the numerator decreased less than the denominator. Therefore, the spike in dependence was actually caused by a *reduction* in export demand, rather than an increase.

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[3] Reductions ranged from $200 in Moldova to $525.6M in the United States. In terms relative to 2004 levels of demand, the reduction ranged from 0.01% in Qatar to 33.8% in Turkmenistan.

Unsurprisingly, major European exporters of TE (i.e. Germany and France) rely most on the English Strait and the Strait of Gibraltar for the outflow of their products. The reliance on the English Strait is particularly high for both producers. The reliance on the Strait of Gibraltar, however, is not as high as expected, given that transit through this chokepoint is necessary for access to importers in Asia and the Middle East. The reason for this relatively low dependence on the Strait of Gibraltar is that the bulk of European TE is traded intra-regionally. For instance, in 2015, 73.8% of TE exports from Germany and 78.4% of exports from France were destined for another European country. The robust regional economy in Europe partly shields its exporters from additional chokepoint risk. However, this is only in terms of the *outflow* of TE from these major producers. Because of the globalized nature of the TE supply chain, these countries may depend more on these chokepoints when they are used to provide inputs to TE manufacturing activity.

4.4.2.2 Inputs to transport equipment manufacturing

Figure 18, below, illustrates chokepoint dependence as the share of the input required to produce one-unit output of TE (s_L). Here, the results for two countries are highlighted in particular: Germany and the United States, the two largest exporters of TE in 2015 (together accounting for 29.2% of total TE exports) with distinctive patterns of chokepoint dependence between 1995-2015.

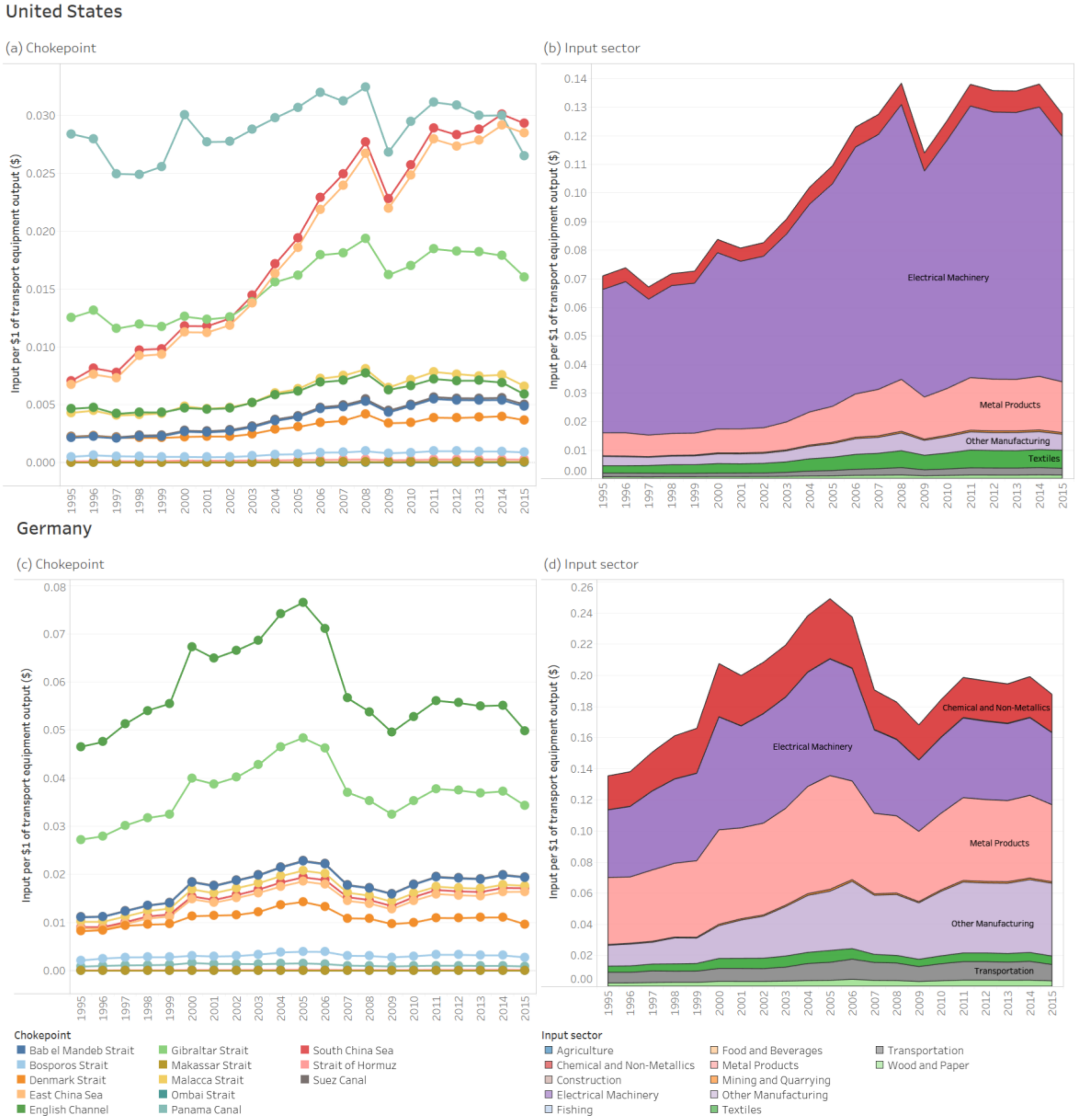


Figure 18. Chokepoint dependence of the transport equipment sector in the United States and Germany. The top panel presents results for the United States. The bottom panel presents results for Germany. (a) and (c) are broken out by chokepoint, while (b) and (d) are broken out by input sector. Note that the sum of all of the lines in (a) and (c) would be equivalent to the area graphs of (b) and (d).

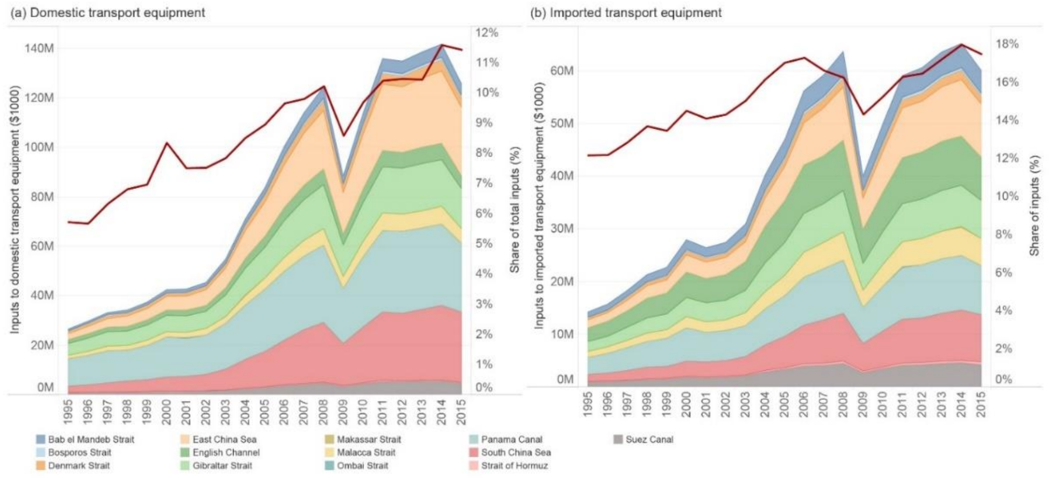
Similarly to its exports, inputs to Germany's TE sector rely on transit through the two major European straits (English Channel and the Strait of Gibraltar). It is also significantly more dependent on the English Channel than it is on the Strait of Gibraltar for these inputs. This again is because while Germany requires transit through the Strait of Gibraltar for access to Asia and the Middle East, it requires the English Channel for intra-regional trade within Europe. Furthermore, roughly 20% of the total input to German cars was produced in other European countries. Most of the inputs are metal products and electrical machinery. Starting in 1999, there is an increase in the inputs from "Other Manufacturing", which includes plastics, rubber, and final products (e.g. furniture, clocks). This is driven by increased imports in these products from China, which grew six times over 1995-2015. At the same time, there was a corresponding reduction in imports of electrical machinery from East Asia (excluding China). This is why there is not a corresponding increase in the dependence on the Strait of Gibraltar; the trends in these two input sectors effectively cancel each other out.

The TE sector in the United States has experienced a dramatic increase in its dependence on the South and East China Seas for its inputs. This is entirely driven by the increase in inputs from China. In fact, if Chinese inputs into the U.S. TE sector were removed, the dependences on the South and East China Seas become lower than the dependence on the Strait of Gibraltar. Between 1995 and 2015, inputs of electrical machinery from China increased nearly ten times. China was by far the largest supplier of electrical machinery inputs into the American transport sector when total inputs (i.e. direct + indirect inputs) are considered. Inputs of metal products were more evenly divided between China and Europe; however, while European inputs have been consistently large over the period between 1995-2015, Chinese inputs increased substantially starting in 2002. This highlights the increasing exposure of the U.S. TE supply chain to disruptions in these chokepoints.

As highlighted by the United States, increased dependence on the South and East China Seas is not only caused by the direct inputs of Chinese products into the TE sector. It is also caused by the inputs of these products into a multitude of manufacturing sectors (e.g. electrical machinery), many of which are used at some point along the TE supply chain. How these three factors influence chokepoint dependence varies by country. For inputs into TE manufacturing, chokepoint dependence ranges from 36.3% in Japan (in 1999, on the East China Sea) to 60.7% in Mexico (in 2000, on the Panama Canal). For outputs of TE from these producers, chokepoint dependence ranges from 50.4% in China (in 1995, on the South China Sea) to 58.2% in Mexico (in 2000, on the Panama Canal).

4.4.3 Transport equipment consumers

The chokepoint dependence of the United States' consumption of TE is given in Figure 19, below.


(a) Domestic transport equipment

(b) Imported transport equipment

(c) Change in final demand and bilateral sector transactions

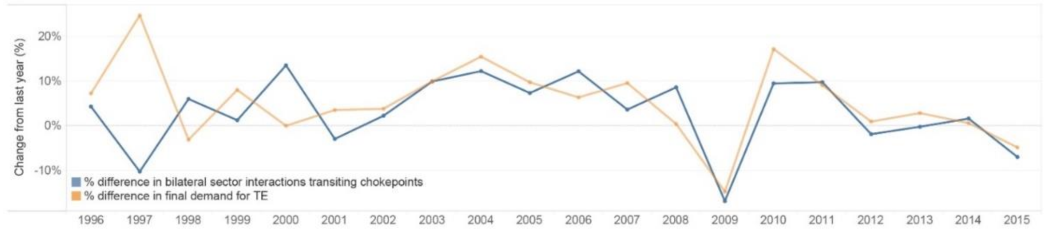


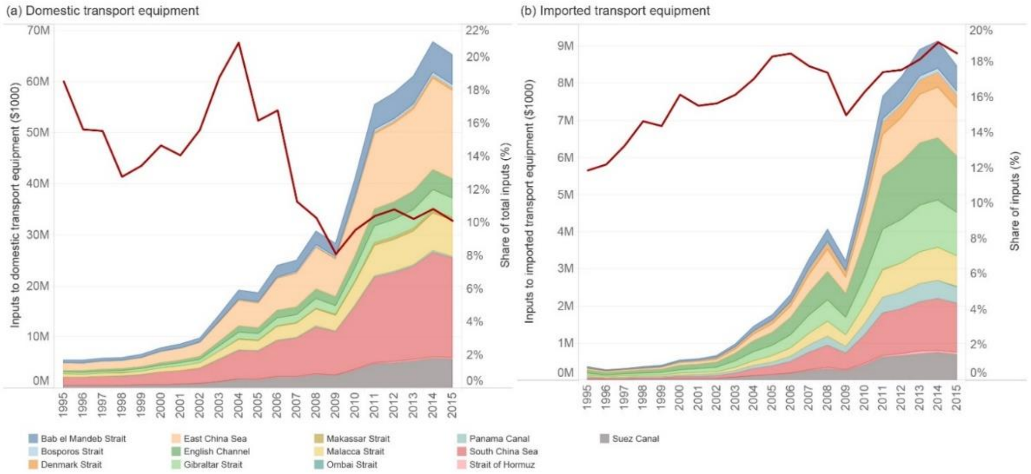
Figure 19. Chokepoint dependence of U.S. consumption of transport equipment. The red line represents the share of total inputs into the production of domestic (left panel) or imported (right panel) transport equipment. The area graph represents the total inputs to the production that necessitates transit through a chokepoint, which are identified by color. Dependence here is given by the red line, which represents the estimate of total imports requiring chokepoint transit divided by total imports to meet TE demand. The stacked area figure represents the total imports used to meet TE demand that transits chokepoints, in thousands of USD. This is equivalent to $\boldsymbol{x^C}$ in Section 4.3.3. The left panel (a) illustrates both of these metrics to meet the household demand for domestically-produced TE. The right panel (b) illustrates the same metrics to meet household demand for imported TE. In other words, it represents the chokepoint dependence of the TE supply chain all the way up to the final assembly and manufacture of the equipment itself. (c) illustrates the year-on-year changes in sectoral transactions that require chokepoint transit (blue) and final demand (orange).

In the United States, 12-17% of inputs into imported TE transits a chokepoint. This is illustrated in the right panel. This dependence has increased over time, with growth slowing from 2005 and observing a dip during the Global Recession in 2009. Prior to 2003, most TE (in terms of value) transited the Panama Canal, followed by the Strait of Gibraltar. By 2007, the latter was surpassed by the East China Sea. This was primarily driven by increased imports from East Asian countries, excluding China. By 2014, the South China Sea also surpassed the Strait of Gibraltar in terms of total value transited. This is driven by the emergence of China as the major global manufacturing hub. The rise in U.S. dependence on the South and East China Seas for its *imported* TE has two components. The first is that the share of TE imports that is manufactured in China and other East Asian countries increased during this time. The second is that the chokepoint dependence of *inputs* to TE manufacturing in East Asia, including China, have also increased over this period. This dependence reverberates through the TE supply chain to ultimately impact the TE consumer, in this case the United States.

Between 1995 and 2015, 6-11% of inputs to the United States' domestic TE sector transited a chokepoint. These are imported inputs from other sectors (e.g. electrical machinery) that are required to produce domestic TE and is represented in the left panel of Figure 19. The overall chokepoint dependence of domestically produced TE has increased more linearly than it has for imported TE. This increase is also relatively consistent across chokepoints, though it is particularly pronounced for the East and

South China Seas, as evidenced by the stacked area graph in the left panel. Both chokepoint dependence (the red line) and total chokepoint transit (the stacked area graph) are increasing over time. This suggests that the patterns in total inputs through chokepoints are not simply driven by increased consumption of TE (i.e. economic growth). If this were the case, the area graph would show an increase but the chokepoint dependence would stay constant. Rather, these patterns are driven by changes in which inputs go into the TE demanded by U.S. households. This is illustrated further in Figure 19c, which presents the year-on-year change in final demand vs. sectoral transactions. Results indicate that these two move in both positive and negative directions over the time period of analysis; therefore, economic growth (proxied by final demand) is not the main factor driving increased chokepoint dependence.

Like the United States, China's chokepoint dependence has increased over the period of our analysis. The total inputs (in thousands USD) used to produce TE in and for China has increased dramatically, and this is reflected in the amount transiting chokepoints. Figure 20 below illustrates the total inputs going into the manufacture of TE in stacked area graphs differentiated by chokepoint. These inputs are what are required to meet the household demand for TE in China.



(c) Change in final demand and bilateral sector transactions

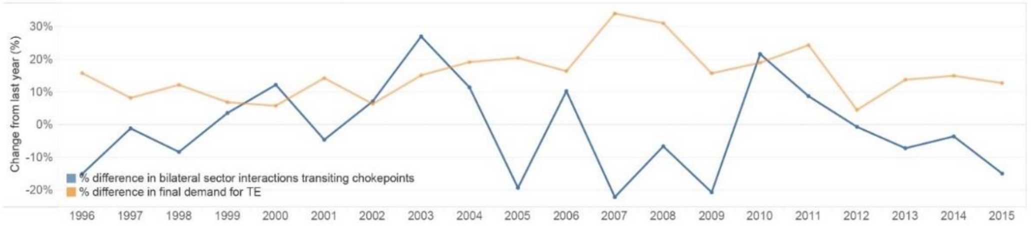


Figure 20. Chokepoint dependence of Chinese consumption of transport equipment. The red line represents the share of total inputs into the production of domestic (a) or imported (b) transport equipment. The area graph represents the total inputs to the production that necessitates transit through a chokepoint, which are identified by color. The bottom panel (c) illustrates the year-on-year changes in final demand and bilateral sector interactions. This format is the same as Figure 19, above.

Unlike the United States, the increase in the total amount transiting chokepoints is driven almost entirely by economic growth, and not by a change in how sectors interact with one another (as represented in the transactions matrix). This can be observed in Figure 20c, which shows that while sector transactions requiring chokepoint transit has moved in both directions over this time, final demand has increased unilaterally. Figures 20a and 20b illustrate that the value transiting chokepoints has increased, but the share of total inputs transiting chokepoints peaks in 2003 and declines (for domestically produced TE) or plateaus (for imported TE). This means that after 2003, China relied more on domestically produced TE or TE imports that do not require chokepoint transit. In other words, China's consumption of domestically-produced TE is largely based on a domestic system of economic inputs. Its consumption of imported TE remains more dependent on chokepoints because TE manufacturing in *other* countries relies more on chokepoints. Therefore, the indirect chokepoint dependence of Chinese household demand for TE is also significantly higher. Note that while the trends in chokepoint dependence illustrated in Figures 19 and 20 may suggest that China is less dependent on chokepoint transit than the United States, the magnitude (i.e. the value) of inputs transiting chokepoints are actually higher in China.

4.4.4 Mapping the global supply chain

To map out the overall supply chain, the transactions matrix (Z) is subsetted to separate out transactions into the TE sector. From there, each of the input sectors into the TE sector are joined with *their* inputs. This is run iteratively to map out each step in the TE supply chain. Weights are applied to each transaction in this procedure. These weights reflect the share of the transaction that correspond to manufacturing TE. For example, say the TE sector uses $100 of textiles output. The textiles sector, in total, produces $200 of output. In other words, 50% of textiles output is used to produce TE. If the textiles sector uses $300 of agricultural output, $150 of this would be linked to the TE sector. A schematic of this design and the resulting transport equipment supply chain for 2015 is presented below. Note that this schematic shows the two final steps in the supply chain for the sake of simplicity. A full representation of the TE supply chain would look more like a network, rather than a pipeline.

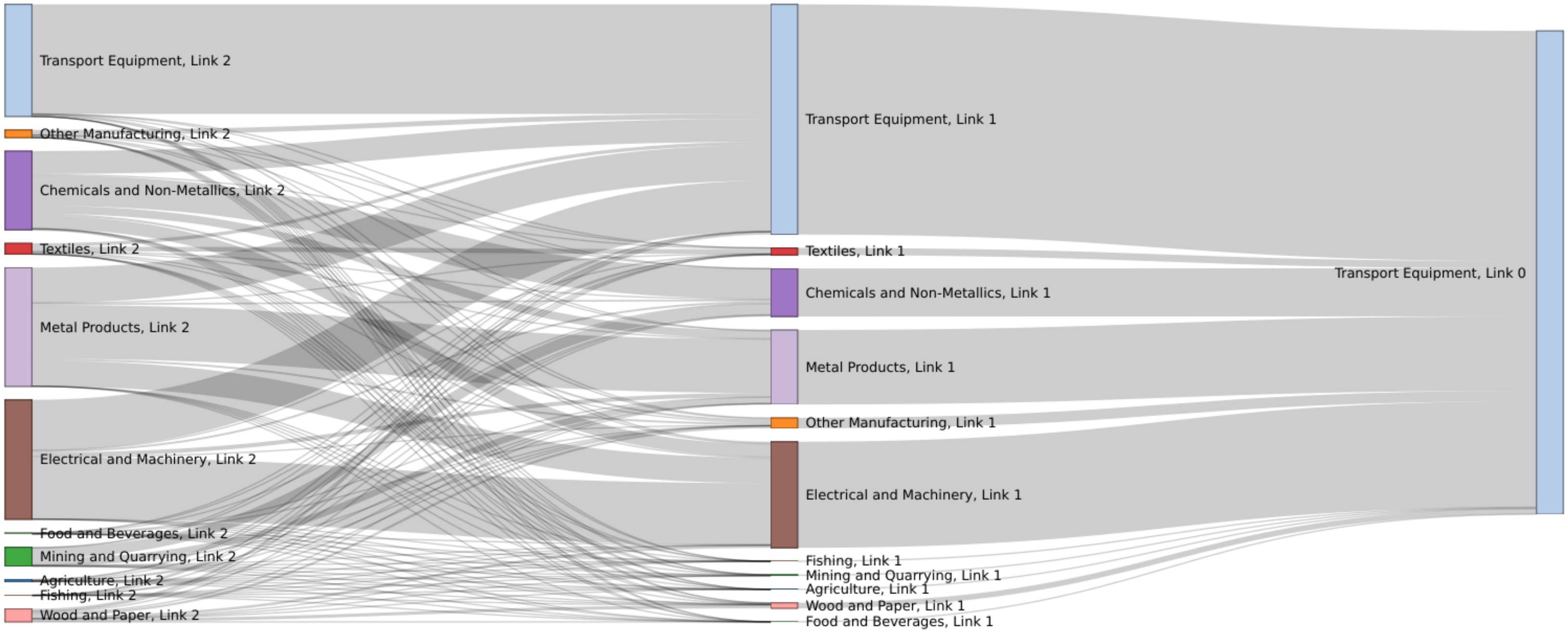


Figure 21. Supply flow diagram of the global TE supply chain (2015). This figure is based on the global transactions matrix ($\boldsymbol{Z}$). Each "Link" represents a link in the supply chain, moving backwards from the final production of TE. A sector can provide input to itself in this diagram, which is why TE output is the largest input into the manufacture of TE. Link 0 represents the transport equipment sector.

This exercise indicates that Electrical and Machinery, Metal Products, and Chemicals and Non-Metallics are the largest inputs into TE manufacturing (Link 1). These sectors are also the largest inputs into manufacturing themselves (Link 2). The original transactions matrix (Z) is substituted with a chokepoint-weighted transactions matrix (Z^V) to visualize chokepoint dependence in the context of the global supply chain. The sum of Z^V across chokepoints is calculated and divided the resulting matrix (element-wise) by Z to obtain a matrix of dependencies. Dependence is therefore a value between 0 and 1 that describes the total chokepoint dependence of a bilateral transaction. To simplify the visualization, these bilateral dependences are aggregated to the region-level and only display the final supply chain link:

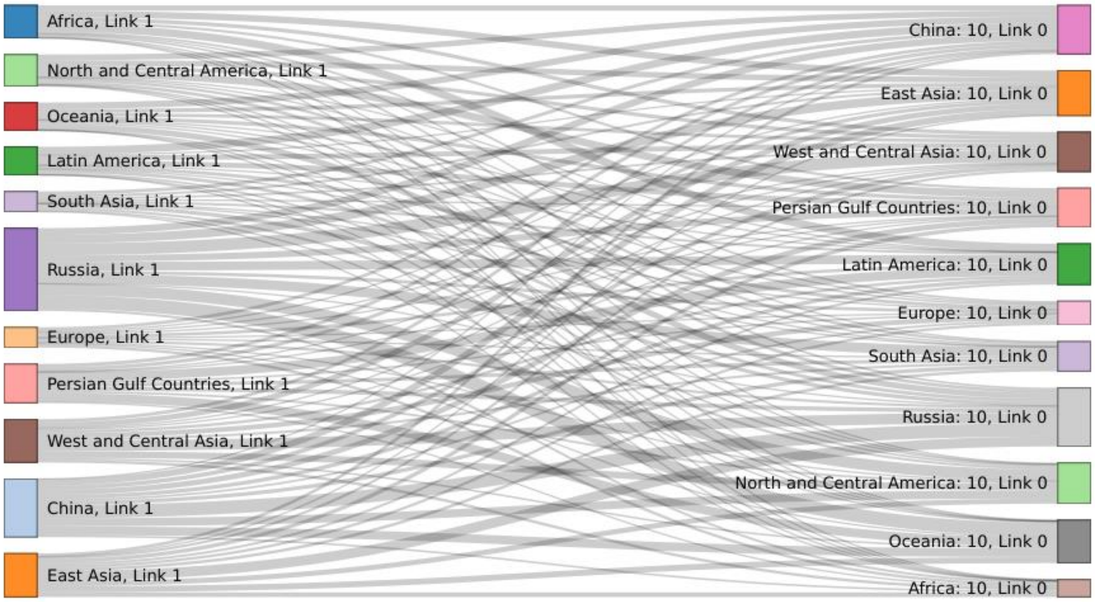


Figure 22. Chokepoint represented through a regional Sankey diagram (2015). Each flow in the Sankey diagram is sized according to the chokepoint dependence of the transaction (i.e. % of transaction transiting through a chokepoint). Transactions are aggregated from the bilateral (i.e. country-sector to country-sector) to the regional level (i.e. region to region) before calculating chokepoint dependence. This is done to simplify this diagram. The nodes (rectangles) are sized according to the total chokepoint dependence of the region's exports (on the left) and imports (on the right). Link 0 represents the transport equipment sector. For example, based on our results, overall transactions from Russia to the transport equipment sector in Oceania is particularly chokepoint dependent.

The key takeaway from Figure 22 is that all regions play a role in global TE supply chain and are therefore chokepoint dependent to varying degrees. Of these regions, Russia, East Asia (excluding China), and China are particularly chokepoint dependent in the TE supply chain. More specifically, the "hot spots" (i.e. the linkages that are most dependent) are: non-energy mining from Russia to East Asia, non-energy mining from Europe to East Asia, and Russian agricultural output to East Asia. The lines in Figure 22 represent the share of each transaction that requires chokepoint transit, not the size of the transaction itself. Therefore, agricultural input, while being chokepoint dependent, is a small input into the TE supply chain. Non-energy mining, on the other hand, is a key input into the TE supply chain. Further, this link between Russia and East Asia represents 9.3% of imported non-energy mining input into East Asia's TE sector. In other words, it is both a critical and vulnerable link in the supply chain.[1]

4.5 Discussion

4.5.1 Limitations of this study

The limitations of this study largely stem from how input-output tables are compiled and aggregated. The multi-regional input-output table used as the basis for HOMIES is the Eora-26 Global Supply Chain Database. This database uses national statistical data where they are available. Where these data are not available, Eora assumes the same economic structure as the closest representative country. Additionally, by nature of aggregating industries to 26 sectors, firm-level heterogeneity is not addressed. The TE sector, in particular, is very complex with firms involved in car manufacturing, aircraft manufacturing, engine manufacturing, and so on. The production process for manufacturing aircrafts is very different from the process of

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From those presented earlier in this section, where chokepoint dependence was measured as the share of either (a) total (direct + indirect) inputs into each sector or (b) the per-unit requirements by each sector.

manufacturing an automobile. Because these industries are aggregated to the higher level of TE manufacturing, the nuances of product-level supply chains are lost. In addition, generally speaking, large scale systemic transitions cannot be captured in input-output tables themselves. To do this, one would need to insert input-output tables into a computable general equilibrium (CGE) model. However, because this study focuses on the history of the TE supply chain from 1995-2015 and, more importantly, because HOMIES compiles a separate table for each year based on the given year's energy and trade data, shifts in economic systems can be captured.

The shortest path algorithm used to compile the chokepoints matrix assumes that each combination of countries has a single shortest route and that trade is conducted along this route. When the shortest route transits a chokepoint, that combination of countries is assumed to require that chokepoint to trade. However, there are many alternative routes that shipping can follow that do not transit a chokepoint. This analysis focuses on the shortest route because it is the cost-minimizing route and, all else equal, is the route most followed. Furthermore, the shortest path algorithm assumes one (and up to three) ports per country. This is because most countries have coasts along one ocean. The single port selected acts as a proxy for other ports along the coast. Where countries have coasts along more than one ocean, a proxy port is selected for each coast.

4.5.2 Chokepoint dependence vs. chokepoint risk

Our analysis thus far has focused on and addressed chokepoint dependence rather than chokepoint *risk*. Whereas dependence can be measured using the metrics outlined in Section 4.3.3, risk is based on a system of variables including geopolitical context, demographics, and climate. Wellesley et al. (2017) provides three dimensions of chokepoint risk: hazard, exposure, and vulnerability (Wellesley et al., 2017). *Hazard* describes the potential causes of disruption, including geopolitical or social unrest. *Exposure* describes the scale of an impact that is likely to be felt by a given population from a hazard. *Vulnerability* describes the local conditions that may mitigate or exacerbate the impact of a disruption. Chokepoint dependence is a measure of vulnerability. This section explores *exposure* in particular to better contextualize our earlier results. Future research can then connect this dimension to *hazards* using additional statistical analysis.

Exposure is addressed in part by the chokepoint dependence metrics s_x and s_L. Exposure increases when overall chokepoint dependence is high *and* a large percent of these imports rely on chokepoint transit. As such, exposure decreases if import dependence is low, even if a large share of these imports relies on chokepoints. An example of the former is Kuwait, which in 2015 imported 90.5% of its TE demand, 94.5% of which required chokepoint transit. An example of the latter is China which, while having a chokepoint dependence of 93.1% for TE, is only 3.8% import dependent. It is therefore less exposed to chokepoint disruptions. A scatterplot of chokepoint dependence vs. import dependence is shown in Figure 23a, below:

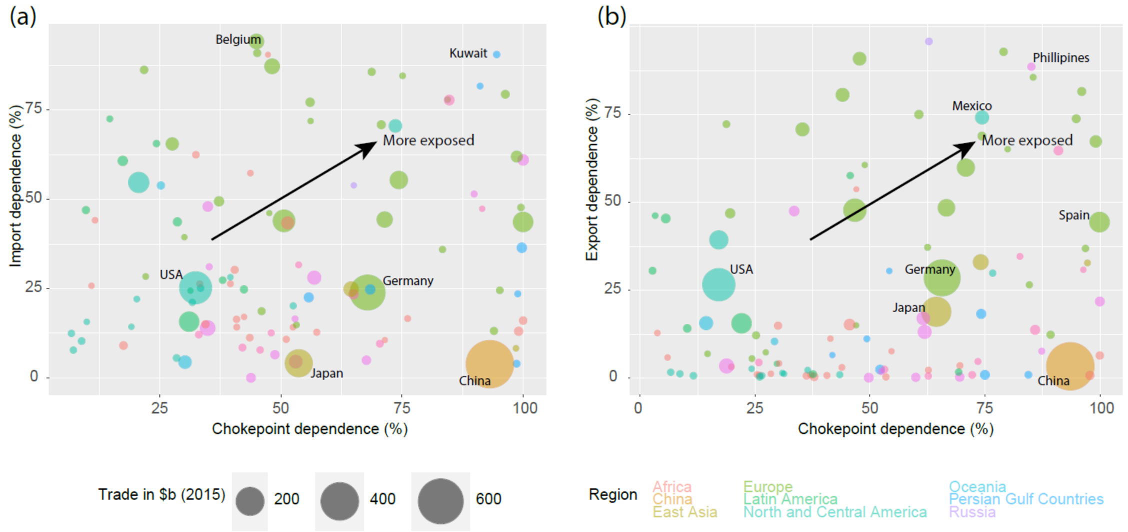

Figure 23. Exposure based on chokepoint and trade dependence. This figure illustrates chokepoint dependence vs. import dependence (a) and export dependence (b) (2015). The points are sized by the value of TE imports (or exports). The points in the top right quadrant represent the countries that are most exposed to chokepoint risk.

The same logic can be applied to exporters of TE. TE exporters that rely on chokepoints for their exports are exposed if they are also export dependent. Our results, in Figure 23b, suggest that the TE exporters that are the most exposed are the Philippines (88.6% export dependence, 85.1% chokepoint dependence) and Finland (81.5% export dependence, 96.1% chokepoint dependence). Of the major exporters, Mexico is particularly exposed (74.2% export dependence, 74.4% chokepoint dependence).

4.5 Conclusion

This study builds on existing literature to examine the chokepoint dependence of the TE sector, which relies on a highly globalized and complex network of manufacturing inputs. This study is the first to explicitly examine the TE supply chain's chokepoint dependence and is also the first to apply an input-output framework to understand trade through chokepoints.

In general, the total dependence of major TE producers on chokepoint transit is a function of (a) economic growth and (b) sectoral interactions throughout the TE supply chain. Economic growth may influence the magnitude of chokepoint transit, but a country's chokepoint dependence will only increase if the production of its TE manufacturing inputs require chokepoint transit. Furthermore, the mechanisms that drive vulnerability in the TE supply chain can vary largely by how a country's sectors interact with one another. This was most apparent in Korea, which experienced a sharp increase in chokepoint dependence because of an increase in its own household demand for domestically produced TE, rather than increases in TE exports abroad. This underscores the need to closely examine the mechanisms that might drive trends in chokepoint dependence.

These mechanisms also apply to the import of TE. For the United States, which exhibits a steady increase in chokepoint dependence from 1995-2015, the trends are largely driven by a corresponding increase in TE imports from East Asia and China.

While the country’s dependence on the Panama Canal has decreased somewhat, its dependence on the South and East China Seas have significantly increased. This is not only because it is importing more TE from China, but also because there is increasing intraregional trade occurring in East Asia that requires these two chokepoints. The direct TE imports from China represents a downstream shift in the TE supply chain. On the other hand, the increase in intraregional trade represents an upstream shift in the TE supply chain; the inputs to TE manufacturing require chokepoint transit and this dependence propagates downstream. For China, the total value of TE imports that transits chokepoints has increased but the share of this value over total TE imports has not. This suggests that economic growth is the key driver of increased chokepoint transits in China.

The ability to maintain reliable supply chains for TE will be even more crucial as the global demand for transportation services continues to rapidly increase. A chokepoint disruption represents just one risk to the TE supply chain, but it is a risk that is often overlooked outside of the energy security and food security literature. The importance of examining chokepoint dependence and risk will also increase as the global market shifts away from internal combustion engines (ICE) to electric vehicles (EV). The materials used to produce ICE drivetrains are very different from the materials used to produce EV drivetrains (Hawkins et al., 2013). In the former, the main material inputs are steel (53% by weight) and iron (13%), largely to support the production of its engine (Dai et al., 2016). In the latter, the design will be based on the battery. The battery, based on current technologies, would require more copper, aluminum, and rare earth minerals than is currently used for ICE (Gemechu et al., 2017). This will change the economic system that supports the TE supply chain as well as the chokepoints that it relies on. This intersection of supply chain risk analysis and technological transitions is an important area for future research.

5 Conclusion

This work uses statistical methods and input-output analysis to examine energy security in the context of international trade. The first study applies econometric methods to estimate the effects of chokepoint disruptions on fuel exports from the Persian Gulf region. The second study introduces HOMIES, a database and model that traces energy flows through the global economy from their production source to their consumption sink. HOMIES is used to re-examine widely-used energy security metrics including trade dependence and the Herfindahl-Hirschman Index (HHI). Finally, the third study applies HOMIES to the global transport equipment supply chain and evaluates the chokepoint dependence of major exporters and importers. This exercise identifies potential areas of increased risk as the supply chain expands to meet the growing demand for transportation.

A major theme in this dissertation is the effect of chokepoint risks on the global economy, particularly in the context of energy security. Wellesley et al. (2015) describes chokepoint risk as having three key dimensions: vulnerability, exposure, and hazard. Chapter 2 evaluated one type of hazard by estimating the historical effects of maritime piracy in the Strait of Hormuz and their implications for energy export security. Maritime piracy tends to be a low-grade hazard, and since 2011 the frequency of piracy events has gone down in and around the Strait of Hormuz (International Maritime Bureau, 2018). Yet maritime piracy is often a symptom of larger economic shocks, environmental degradation, and failures in governance. Somali piracy increased in the mid-2000s as a result of droughts and subsequent economic hardship (Ploch et al., 2011; Silva, 2010). Most recently, the COVID-19 pandemic has caused a global economic shock that has led to increased reports of piracy in and around key maritime chokepoints (Drew, 2020; Prins, 2020). And as climate change exacerbates already dire economic conditions, we may see an uptick in maritime piracy that disrupts energy supply chains. The global shift away from fossil fuels and toward alternative energy resources can reduce the vulnerability of the global energy system. At the same time, it may increase the vulnerability of fossil fuel supply chains as national governments invest less in securing maritime chokepoints.

Chapter 4 evaluated the chokepoint dependence of the global transport equipment supply chain. Chokepoint dependence is a measure of vulnerability in the supply chain, and describes whether and how trade conditions can mitigate or exacerbate the impact of a disruption. Chokepoint dependence alone is not a measure of chokepoint risk. However, it is still a useful metric for policymakers to have as they look to meet the rapidly increasing global demand for transportation. All participants in the transport equipment supply chain are chokepoint dependent. However, the drivers of this dependence vary based on economic growth and shifts in underlying economic systems. This latter driver can be captured because HOMIES includes data spanning 20 years, from 1995-2015. Furthermore, a country’s chokepoint dependence is not only determined by changes in their direct supply chains, but also by shifts in adjacent supply chains. For example, the United States' increased dependence on the South China Sea was not only a product of increased imports from China, but also a product of increased intraregional trade in East Asia. It is crucial for policymakers to understand that simply cutting trade ties with one nation does not disconnect a country from supply chains and the risks inherent in them.

HOMIES is a major contribution of this work. It is built entirely from publicly available data and is intended to be open-access and open-source. In other words, it is a starting point for future research. The first of this research should be the continued refining, validation, and development of the database itself. The data compilation for HOMIES relies heavily on large databases published by international organizations like the International Energy Agency. Often, these organizations rely on national statistical agencies for their data. Measurement error can therefore arise due to different levels of rigor for data collection. Additionally, calibration and validation processes differ by international organization. The resulting uncertainties can compound as we estimate direct and indirect energy flows. It will be a difficult but important exercise to understand these uncertainties and the limitations that they present.

Finally, results from HOMIES are snapshots of the global economy from 1995-2015. The model does not make future projections. It also can only be as current as the most recent year that all underlying datasets are published and publicly available (which, to date, is 2015). A next step for this work would be to incorporate HOMIES into a larger model, such as a computable general equilibrium (CGE) model, that can use historical data to estimate the effects of economic and energy shocks in the future. Methodological developments in input-output analysis also point to promising ways that input-output data can be imputed and forecasted (Lenzen et al., 2012b; Long and Wang, 2012). However, these advancements, in their current form, can only be applied if the world experiences incremental changes that do not completely change the way that nations and industries interact with one another. In the last few months, we have witnessed how quickly and how much the global economy can shut down and shift due to COVID-19. Technological transitions in global energy systems will also fundamentally change the energy resources that are traded and the industries that are demanded. Future research in energy systems and input-output analysis will need to be able to address these large-scale systemic shifts.

Appendix A Supplementary Material for Chapter 2

The Supplementary Material for *"Maritime piracy in the Strait of Hormuz and implications of energy export security"* can be found at the following link:

https://github.com/junukitashepard/dissertation_files/tree/master/Chapter2

Appendix B Supplementary Material for Chapter 3

The Supplementary Material for *"Hybrid input-output analysis of embodied energy security"* can be found at the following link:

https://github.com/junukitashepard/dissertation_files/tree/master/Chapter3

The link to the Github repository associated with HOMIES development can be found at the following link:

https://github.com/junukitashepard/homies

Appendix C Supplementary Material for Chapter 4

The Supplementary Material for *"The Dependence of the Global Transport Equipment Sector on Maritime Chokepoints: A hybrid-input output approach"* can be found at the following link:

https://github.com/junukitashepard/dissertation_files/tree/master/Chapter4

Appendix D Additional chapter

An additional chapter on climate and trade policies, titled *"Effects of climate and trade policies on future global energy trade networks"* can be found at the following link:

https://github.com/junukitashepard/dissertation_files/tree/master/Additional_Chapter

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Biography

Jun Ukita Shepard received an A.B. from Harvard University in Environmental Science and Public Policy (2014). She received an MPhil in Environmental Policy from the University of Cambridge (2015) before spending two years at Brown University as a research fellow in the Economics department. She started her PhD at Duke University in the Division of Earth and Ocean Sciences in 2017. She was awarded the James B. Duke Fellowship from Duke Graduate School and the Energy Data Analytics Fellowship from Duke Energy Initiative and the Sloan Foundation. Her first peer-reviewed article appeared in *Energy Policy* in 2020 and is the first study in this dissertation ("Maritime piracy in the Strait of Hormuz and implications of energy export security"). Additional articles include "Hybrid Input-Output Analysis of Embodied Energy Security" and "Effects of climate and trade policies on future global energy trade networks", both currently under revision at *Applied Energy*. In 2019, she received a summer research fellowship at the International Institute of Applied Systems Analysis (IIASA), where she was funded by the National Academy of Sciences.