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Effects of Import Constraint due to Security of Supply Reason on the Carbon Leakage

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Zusammenfassung

Diese angewandte Studie untersucht das Carbon-Leakage-Problem im Hinblick auf zwei Aspekte und zieht Schlussfolgerungen, ob die Carbon Leakage möglicherweise nicht so gravierend ist, wie es in der Literatur, die das Carbon-Leakage-Problem mit zwei verschmutzenden Energien untersucht, vorgesehen ist. Der erste Aspekt befasst sich mit der Frage, wie sich die durch die positive Ausstattungsänderung bei Erdgas verursachte Leakage im grundlegenden ressourcenökonomischen System auswirkt, in dem Kohle und Erdgas für alle Marktteilnehmer vollkommen substituierbare Güter sind. Der zweite Aspekt befasst sich mit den Auswirkungen einer Importquote auf den globalen Energiehandel und dem Carbon-Leakage-Problem.

Es ist bekannt, dass die Shale-Gas-Revolution in den USA zu einer Ausweitung des US-Kohlehandels geführt hat. Während der Studie nutze ich den Kohle- und Erdgashandel aus den USA in die Welt, insbesondere zu großen Importeuren wie China und Europa, um das Zusammenspiel dieser beiden Energien nach dem Shale-Gas-Boom zu beobachten. Darüber hinaus befasst sich die mögliche Einführung von Importquoten für die US-Kohle durch China aufgrund der Sorge um die Versorgungssicherheit mit der zweiten Frage dieser Studie und zeigt ihre Auswirkungen auf das sich verändernde Muster im Energiehandel.

Nach meinem besten Wissen wurde in der gesamten Literatur über Carbon Leakage bisher der Handel untersucht, der von den Faktoren der Angebotsseite beeinflusst wird, und die Nachfrageseite nur durch die Entscheidung über die Importnachfrage allein aufgrund der Preisentwicklung einbezogen. Dieses ökonomische System spiegelt nicht die realen Welthandelsmärkte wider. In Wirklichkeit verfügen die importierenden Volkswirtschaften aus verschiedenen Gründen über Instrumente zur Handelshemmnissen wie Zölle und Importquoten. Diese Anreize können als Bedenken für die nationale Sicherheit, des Schutzes der heimischen Kleinkinderindustrie und des Importschutzes aufgeführt werden, um eine Diversifizierung der heimischen Industrie zu ermöglichen. In diesem Papier konzentriere ich mich hauptsächlich auf den Grund der Versorgungssicherheit als Motiv für die Einführung von Handelsbarrieren.

Mit der Unterstützung des vorgestellten Modells und der empirischen Daten über den Kohle- und Erdgasmarkt der Vereinigten Staaten und Chinas werden in diesem Papier zwei Aspekte hervorgehoben: Erstens induziert das Wirtschaftssystem die Kohle-Gas-Substitution in einem Umfeld, in dem die großen Volkswirtschaften in der Lage sind, zwischen beiden Energien umzuschalten, was die Verlagerung von CO2-Emissionen verlangsamt. Zweitens setzen Nationen, die Bedenken hinsichtlich der Versorgungssicherheit haben, in der Tat Handelsbarrieren ein, die die globalen Energiemärkte erheblich beeinflussen. Die vorliegende Studie will auf diese Lücke in der Carbon-Leakage-Literatur hinweisen, indem sie darauf hinweist, dass die von den importierenden Volkswirtschaften eingeführten Handelsbarrieren berücksichtigt werden müssen, da diese erhebliche Auswirkungen auf die Energiemärkte haben. Eine Implementierung einer Importquote für den Kohlehandel - wie sie von China für die US-Kohle praktiziert wurde - konsolidiert die Verlangsamung der Verlagerung von CO2-Emissionen, die durch den Substitutionseffekt im Wirtschaftssystem verursacht wird, weiter.

Contents

1. Introduction

It is well-known that after the Shale Gas Boom in the United States, carbon leakage to the developing Asia has mitigated the emission reductions achieved in the U.S. domestic market to a certain degree. There is a consensus that in order to alleviate the climate problem, the global implementation of some sort of emission reduction measure is required which is also currently not realistic. Nevertheless, it is argued that the carbon leakage problem in the power generation sector might get decelerated by the coal-to-gas substitution. The global arising pattern in the energy markets moves towards the increasing competitiveness and liquidity on the global LNG markets especially as the result of the cheaper international supply and higher demand for natural gas that is a cleaner fuel source in terms of CO2 emission. Thus, the magnitude of carbon leakage on the long-term with the substitution effect taken into account is an ongoing research area.

This applied study examines the carbon leakage problem with regards to two aspects and draws conclusions on whether the leakage may not be as severe as it is foreseen in the literature that studies the carbon leakage problem with two polluting energies. The first aspect deals with how the carbon leakage induced by the endowment change in natural gas plays out in the basic resource economics system where coal and natural gas are perfectly substitutable goods for all market participants. The second aspect tackles with the effect of an import quota on the global energy trade and the carbon leakage problem. It is well-known that the Shale Gas Revolution in the U.S. has led to the expansion of U.S. coal trade. During the study, I use the coal and natural gas trade from the U.S. to the world especially to major importers such as China and Europe to observe the interplay between these two energies in the aftermath of Shale Gas Boom. Further, the possible import quota implementation by China on the U.S. coal due to the security of supply concern starting from the year 2015 addresses the second question of this study and exhibits its impact on the changing pattern in the energy trade.

The carbon leakage literature mainly studies the extent of environmental impact in terms of CO2 content of the fuel source. Combustion of natural gas emits CO2 as half as of coal. However, the exact methane leakage rate at the production level of gas is unknown and the actual contribution of natural gas to global warming is a part of the ongoing study. This gives natural gas its uncertain role as a cleaner energy compared to coal. In alignment with the rest of the carbon leakage literature, this paper assumes away natural gas as the cleaner fuel alternative to coal in terms of CO2 emission.

To the best of my knowledge, the carbon leakage has been studied by two strands of literature. One part of the literature has dealt with the limitation of the effectiveness of climate policy commitments' under different settings. It is argued that such commitments' effectiveness is limited with one polluting source, however it does not lead to a leakage rate higher than 100% - see, Eichner and Pethig (2011), Ritter and Schopf (2014), and Fischer and Salant (2017). This stream of literature has been extended by allowing the emissions from more than one carbon energy source - see, Chakravorty, Moreaux and Tidball (2008), Henriet and Schubert (2015), and Coulomb and Henriet (2014). These studies have dealt with the question whether such climate commitments at the world level may limit carbon leakage in a closed economy setting. Daubanes, Henriet and Schubert (2017) extend this part of literature for open economy setting with an unilateral climate commitment and they argue that such policies may turn counterproductive when there are more than one carbon source, which is referred as “green paradox” by Sinn (2008). They indeed find that the climate policy may cause a leakage rate higher than 100% and increase the overall global carbon emission. To conclude, these studies demonstrate that carbon leakage counteracts the effectiveness of climate policy commitments or may even offset the emission reduction under the existence of more than one polluting source.

The other stream of the literature has focused on the resource economics. Wolak (2016) has developed a spatial equilibrium model to evaluate the effects of Shale Gas Boom on the global coal market allowing for coal-gas substitution in the United States and Europe. He finds the cross elasticity of coal consumption to gas price approximately to 0.18 in Europe. He further finds that Shale Gas Revolution has significant effect on reductions in coal consumption in the U.S. and Europe and this effect might get reversed as Shale Gas Boom ends. He implies that the increase in U.S. coal exports contributes directly to the global emission reductions and indirectly reductions from Europe by inducing coal-to-gas substitution. He assumes that only Europe and the U.S. are able to switch between coal and natural gas while China modelled as a monopsony buyer consuming only coal. Knittel, Metaxoglou, Soderbery and Trinidade (2018) have studied whether carbon leakage induced by the Shale Gas Revolution in the U.S. has increased the global coal trade and contributed to coal linked CO2 emission increase or replaced the coal trade from other exporting economies. They used counterfactual analysis how the coal trade would change in the absence of the Shale Gas Revolution and find the quantity traded is only 0.14% lower than the actual coal trade (p. 5). They conclude that the Shale Gas Revolution did not have a significant effect on the carbon leakage to the world.

This paper refers to the study of Daubanes et al. (2017) by pointing out that the leakage rate may not reach to the extent that is expected under an unilateral policy commitment setting with two pollutant sources. The first contribution of this paper indicates that the coal trade will be constrained by the economic system solely due to the substitution effect induced by the global expansion of the natural gas market. I use a general equilibrium model that follows a similar approach of Wolak (2016) and Knittel et al. (2018). Within the model framework of this study, both exporting and importing economies can substitute between coal and natural gas. Both parties can produce coal, whereas only the exporting economy can produce and export natural gas which are produced with decreasing and increasing returns to scale, respectively. I analytically show that the scale up of natural gas production leads to the saturation of the domestic market in the exporting economy. Ultimately, the abundant natural gas supply leaks into the international market and replaces the coal market to a certain extent. Finally, with the increasing availability of natural gas it becomes a more favourable cheaper energy source on the international market and causes the shrinkage of the coal markets on the long-term. I argue that alone in the absence of global growing environmental concerns, the resource economics induce coal-to-gas substitution and constrain the carbon leakage by a certain extent which has been not acknowledged in the study of Daubanes et al. (2017). The positive cross elasticity of coal consumption to gas price in Europe found by Wolak (2016) underpins indeed there is a correlation between the European coal and natural gas markets. This implies that falling natural gas prices reduce coal consumption and substitute coal markets by some degree.

In recent years due to the aggravation of global warming problem, economies such as China and India that heavily use coal as power generation fuel have started to implement climate policies as well. Such climate commitments by major coal importers consolidate and intensify the slowdown of coal-linked CO2 leakage.

The carbon leakage is generally induced due to either the climate policies or the changes in the production technology. To my best knowledge, all the literature on carbon leakage have studied so far the trade influenced by the factors from the supply side and included the demand side only by the import demand decision solely based on the price developments and their respective import demand elasticities. This system of framework does not reflect the real world trade markets. Indeed, consumers make their consumption decisions based on the world prices they perceive. Nevertheless, in reality the importing economies have a wide range of tools to impact the world trade markets. Many countries implement trade constraining instruments such as tariffs and import quotas due to the various reasons. These incentives can be represented as the concerns of national security, protection of domestic infant industry and import protection in order to allow for diversification in the domestic industry.[1] For the nations, importing a large share of its energy from a particular country that might possibly exercise geopolitical power poses a great threat for the security of supply. Similarly, infant industries have comparative disadvantage on the global market against their incumbent foreign rivals with economies of scale. Protection of domestic industry is of highly importance until these infant industries gain the necessary competitiveness. The last and third argument points out that importing goods from certain sectors instead of establishing a domestic industry blocks the opportunity of domestic diversification in that sector, while other countries expand by economies of scale and also by varieties of choice. This creates a significant impediment on the growth of the economy. Due to the given reasons, importing countries use multiple tools to restrict import trade. In this paper, I mainly focus on the security of supply reason as the motive for implementation of trade constraining measures.

Security of energy supply is of highly importance for nations as it has great economic and political consequences. This also means with an increasing energy dependency, nations may exert geopolitical power on one another. To give an example, Russia has exercised a such power on Post-Soviet States as most of them have completely relied on Russian energy supply. A major dispute arose between Russia and Ukraine in 2005 and led to gas disruptions in many European countries since Ukraine serves as a transit country for Russian gas to Europe.[2] Thus, keeping the energy dependency below a certain level is critical. Nations use trade instruments such as tariffs and import quotas on goods which are of crucial importance on the nation's economy and geopolitical security to maintain a diversified and secure supply. This paper emphasizes that nations with security of supply concerns indeed use trade barrier tools that significantly influence the global energy markets. This study aims to refer to this void in the carbon leakage literature by pointing out that the trade barriers implemented by the importing economies require to be taken into consideration since these have significant effects on the energy markets. I show analytically how an import quota on the coal trade affects the energy markets and further contributes to the limitation of coal linked carbon leakage.

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[1] See Root (2000) cited in Ma & Lu (2011), p. 72

[2] Wikipedia. Russia-Ukraine gas disputes. Retrieved from: https://en.wikipedia.org/wiki/Russia%E2%80%93Ukraine_gas_disputes.

The rest of the paper is structured as follows. In Section 2, I describe and interpret the data based on the historical developments in the energy markets. Section 3 presents the general equilibrium model. Afterwards, I proceed with the discussions on how the economic system works within the presented model, the effects of the Shale Gas Revolution and import quota implementation with an analytical approach. In Section 4, the empirical data is interpreted within the framework of the analytical model from Section 3. In Section 5, I review the conclusions and give implications on two main points regarding the future of energy markets: first, the emerging situation on energy trade between Russia and China and, second, the substitution between natural gas and oil as the result of electrification in the transport sector.

2. Empirical Data

2.1 Data Description

To address the first question whether it leads to carbon leakage on the long-term under a trade setting where all market participants are able to switch between coal and gas in the power generation sector, I distinguished between large exporting and importing regions.

In order to observe the effects the Boom ('Shale Gas Boom'), I included the U.S. as the only coal and natural gas supplier in the world market. Along with the U.S., there are large exporters as competitors in the global coal and natural gas markets such as Russia and Australia, which are mentioned in the model section but not included into the empirical data. As for the large importing regions that may substitute between coal and natural gas, I take two regions into consideration: China and Europe, which are amongst the largest consuming regions of coal and natural gas worldwide. European region consists of the EU-28 countries (before Brexit, the UK included), Norway and Switzerland. I added Switzerland to European region as it uses no coal in its energy mix and is a part of the well-connected European natural gas market as an important transit country with Transitgas pipeline. Norway is the third largest natural gas producer in the world and largest natural gas supplier of the UK, which both are well-integrated into European natural gas network.

First I looked at the data that belong to the domestic U.S. coal and natural gas markets to view the changes induced by the Shale Gas Revolution. Figure 1 and Figure 2 depict the U.S. shale gas production in billion cubic feet for the period 2007-2018 and the net natural gas import of the U.S. in million MMcf for the period 2000-2018, respectively.

Then, in order to examine the change in the U.S. energy consumption I constructed Figure 3 which illustrates the market share of coal and natural gas in the U.S. power generation over the period 2001-2019. Figure 4 depict the U.S. coal production, consumption and net export volume in million short ton for the period 2001-2018. I used EIA (U.S. Energy Information Administration) Database as the source for all the data related to the U.S. energy market, which serves an extensive variety of information for all energy resource types.

Secondly, I gathered the coal and natural gas prices in the relevant regions in order to compare the energy markets in different regions and understand the trade between the regions. Figure 5 illustrates the natural gas spot market prices in the U.S. (Henry Hub), the

UK (Heren NBP Index) and average German import price in USD per million Btu for the period 2000-2018 on yearly average. The natural gas contracts are usually indexed with crude oil price, therefore I attached the Brent crude oil price in USD per bbl for the same period in Figure 6. The data from BP Statistical Review of World Energy Report 2019 has been used as source for both figures.

Figure 1. U.S. shale gas production

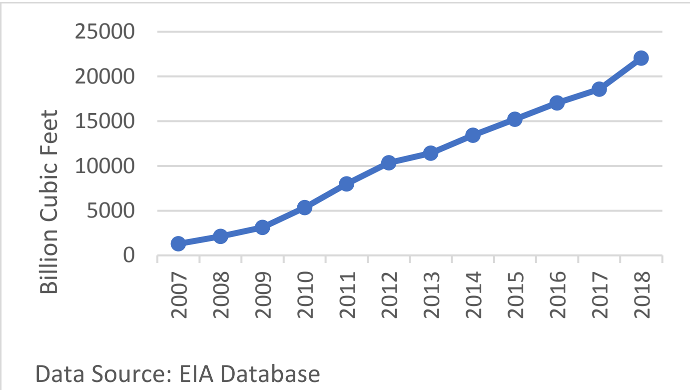


Figure 2. U.S. net natural gas import

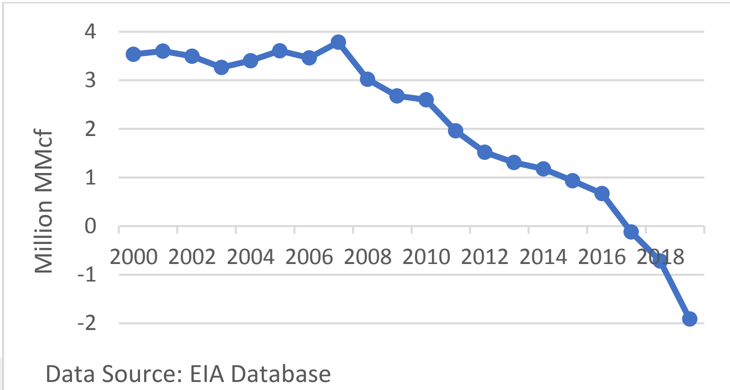


Figure 3. Share of coal and natural gas in the U.S. net generation mix for all sectors

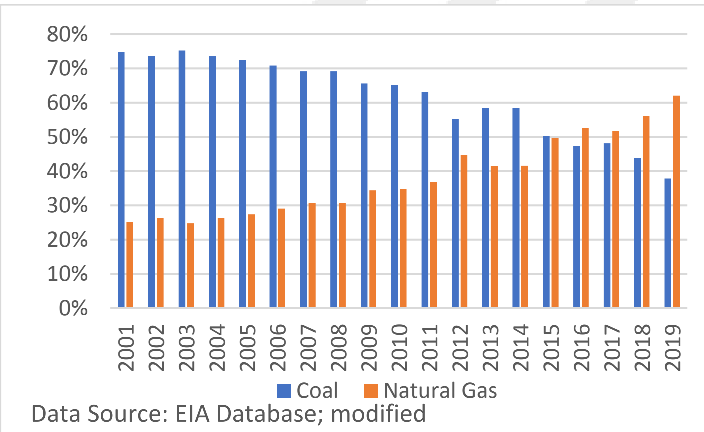
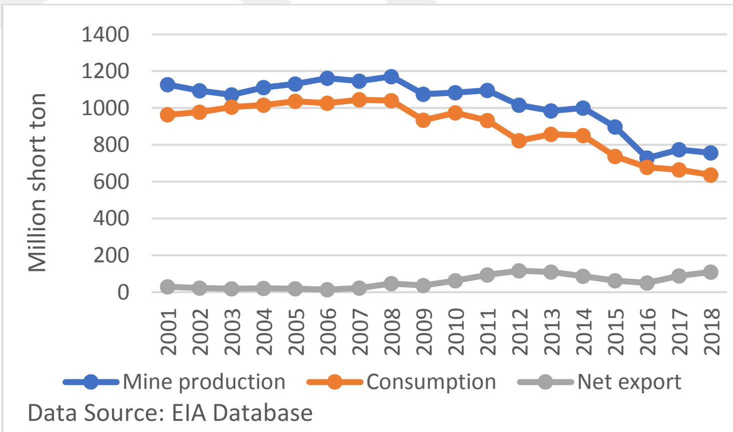


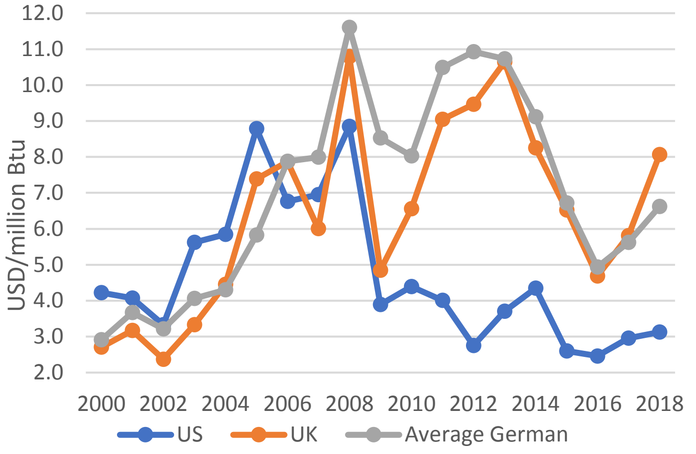
Figure 4. U.S. coal production, consumption and net export volumes



Then, I proceeded with the coal prices in the following regions: U.S. (US Central Appalachian spot price index), China (China Qinhuangdo spot price) and Northwest Europe (Northwest Europe marker price) given in USD per tonne unit taken from BP Report (2019) in Figure 7 and the U.S. LNG export price in USD per thousand cubic feet illustrated in Figure 8 sourced from EIA Database. This enables to develop an intuition for the consumers' perspective on which energy source becomes relatively cheaper and favourable to consume. The price comparison between coal and gas supports the interpretation of the international trade graphs.

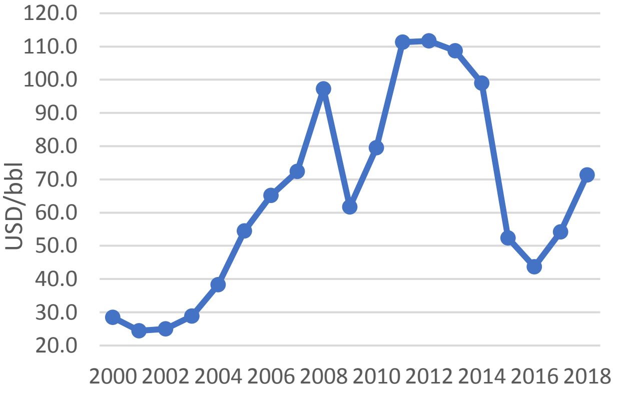
With coal and gas prices in hand, I looked for the trade data that gives the trade quantities from the U.S. to major importers. Figure 9 represents the market share of the U.S. coal importers. The data is sourced from EIA Database and calculated with an approach that is explained in the next subsection. Significant importing regions of the U.S. coal are listed as follows: China, Europe, India and Rest of the World. Figure 10 illustrates the U.S. LNG export volume in million MMcf to major importers. Data is sourced from EIA Database as other data related to the United States. Japan has been neglected in Figure 10 since Japan historically procures LNG from the U.S. prior to the Boom. This has no relevance to the consequences of the Shale Gas Boom in terms of coal and gas trade.

Figure 5. Natural gas spot market prices



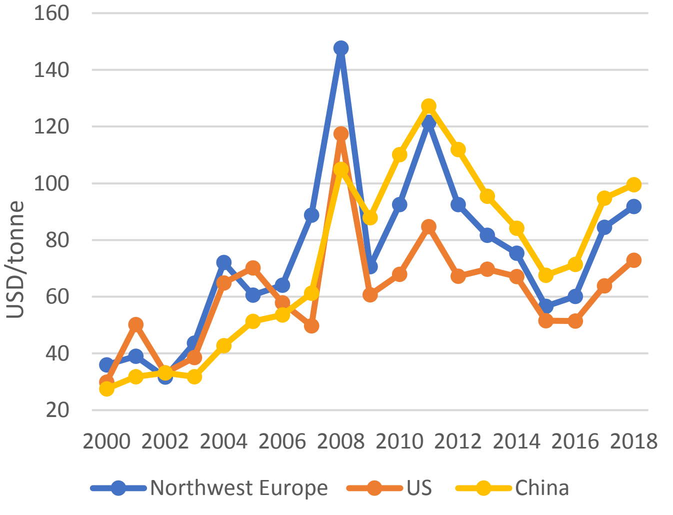
Data source: BP Report (2019)

Figure 6. Brent crude oil price



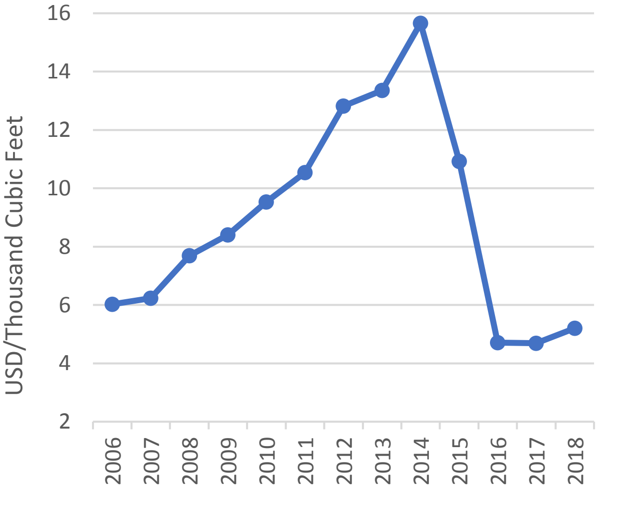
Data source: BP Report (2019)

Figure 7. Coal spot market prices



Data source: BP Report (2019)

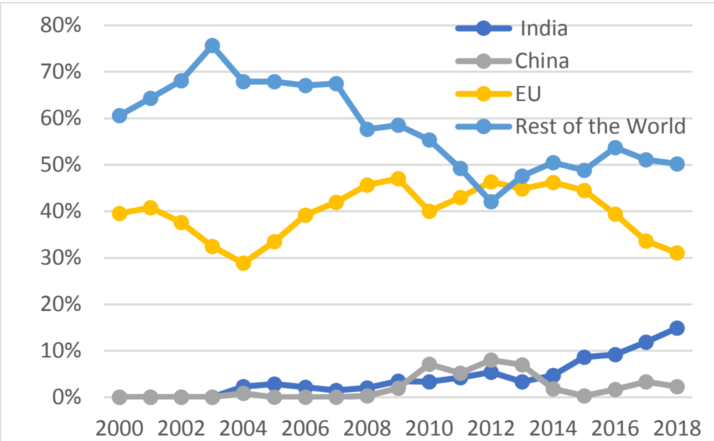
Figure 8. U.S. LNG export average price



Data source: EIA Database

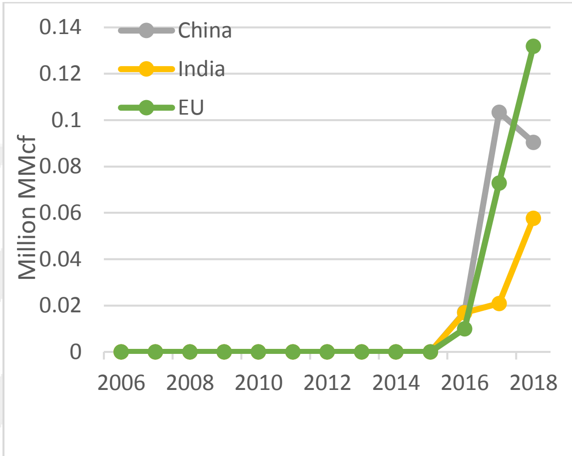
Moving on to the importer side of the global coal trade, finding the data on China's coal import quantity was one of the main difficulties. The exact data on the trade partners of China's coal trade is missing in BP reports, therefore I used UN COMTRADE database (United Nations International Trade Statistics Database). The data is available in monetary unit (thousand US Dollars) value of coal trade transaction. The currency conversion differences are accounted for in the UN COMTRADE database. Figure 11 illustrates the coal suppliers' shares in China's coal import market for the period 2001-2018. The import shares from Australia and Indonesia have been combined together as these are China's two largest coal suppliers historically, even prior to China became a net coal importer. The United States and Russia are included into the data since they are major energy exporting regions that are of this study's interest. The trade pattern of the U.S. has changed after the Boom and Russia seeks an ambitious trade competition with the U.S. as an exporter.

Figure 9. Market share of U.S. coal importers



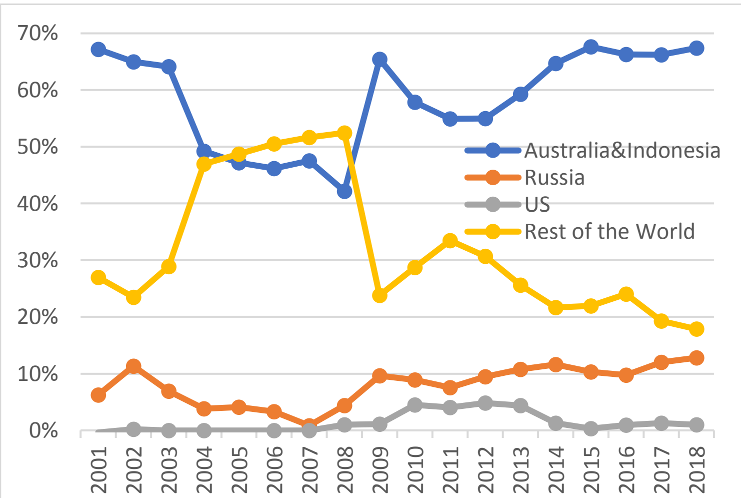
Data Source: EIA Database;
Own calculation explained in Section 2.2

Figure 10. U.S. LNG export volumes



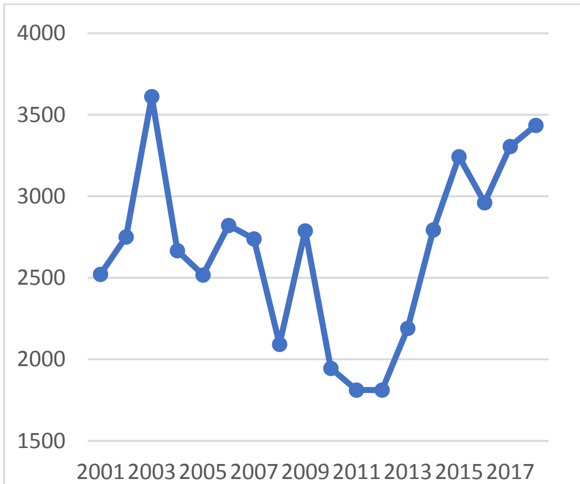
Data source: EIA Database

Figure 11. Market share of coal exporters to China



Data Source: UN COMTRADE Database modified based on EIA Database
Own calculation explained in Section 2.2

Figure 12. HHI of China's coal import market



Data Source: UN COMTRADE Database,
EIA Database;
Own calculation explained in Section 2.2

The UN COMTRADE data for the period 2014-2018 on the U.S. coal export to China has been modified based on the percentage changes in the U.S. coal export volume taken from EIA

Database. The reason for that is the trade values in the UN COMTRADE data is inconsistent with the data from EIA Database and reliable energy articles. The data from UN COMTRADE shows that China has net-exported coal to the U.S. in year 2016 for the first time after China became a net coal importer, whereas EIA Database gives that China has increased U.S. coal import from 229.891 to 995.901 million short tons. Due to the given inconsistency and lack of access to a more reliable data source, I modified China's imported U.S coal data from UN COMTRADE data starting from year 2014 successively corrected by the percentage changes in the corresponding U.S coal export data. To quantify China's security of supply of its coal import market, I used the Herfindahl-Hirschman Index (HHI) as an indicator. Figure 12 shows the HHI of China's coal import market.

I added a separate graph that illustrates U.S. share in China's coal import market to represent the change in coal trade after the Shale Gas Boom given in Figure 13. Figure 14 shows the U.S. steam coal export price to China and the average export price sourced from EIA Database in addition to Chinese spot market price from the BP Report (2019). The U.S. export price to China gives the price that Chinese consumers receive for the U.S. coal. Figure 14 exhibits clearly the price difference of Chinese spot coal price and the price of imported U.S. coal. This price difference later on serves as a tool to interpret the coal trade between the U.S. and China.

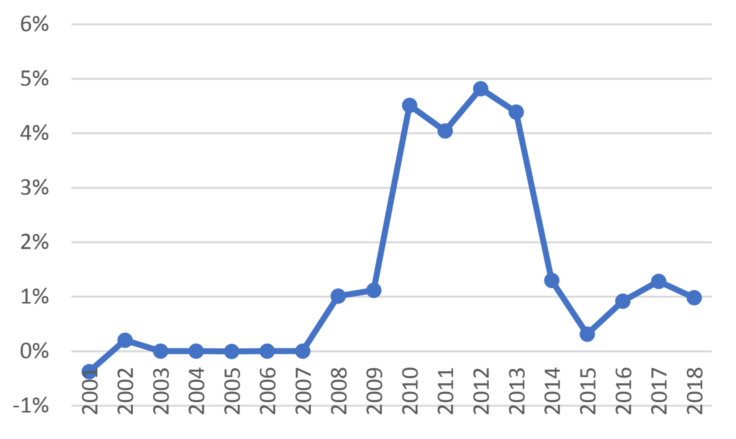
To exemplify the trade barriers due to security of supply consideration, I included the natural gas import market of European region into the empirical data as the security of supply concern is rather explicitly documented. The data regarding European region is taken from Eurostat Database. Figure 15 illustrates the share of natural gas (both pipeline and LNG) suppliers to European region. The major suppliers are determined as Russia, Algeria along with the supply from European region mainly from Norway and the UK. The United States has been included to illustrate the changing LNG purchase profile of Europe. Additionally, Figure 16 depicts the HHI of European natural gas import market.

In addition to European region, Spain implements the import quota formally. For its illustration, Figure 17 and Figure 18 give exporters' share in Spain's natural gas import market and HHI, respectively. In the data, Trinidad Tobago and Peru are combined into 'South America' and 'Rest of the World' consists of Angola, Cameroon, Egypt, Libya and Oman, which have contributed to the Spanish natural gas supply market with very small share since 2012.

The approach for handling with the missing data is either by taking the average of its predecessor and successor years' value or by finding a proportioned value based on the data from another database with another unit of measure for the corresponding year.

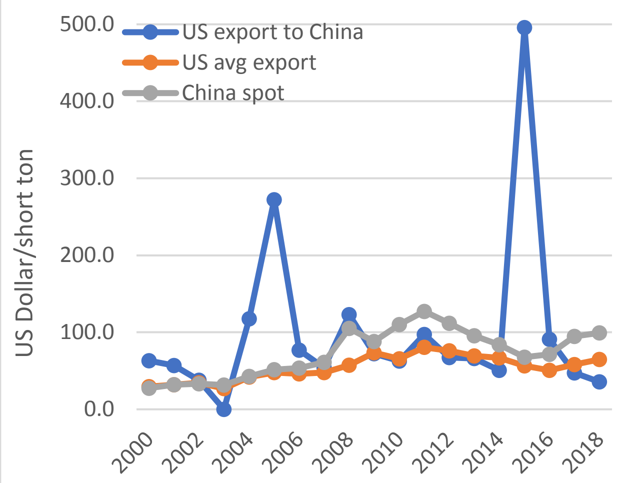
Another difficulty during the study lies in finding references with regards to informal trade restrictions especially the import quotas. Nations prefer not to publish such measures explicitly in order to avoid geopolitical and economic consequences such as the execution of a similar measure and retaliation possibility in the same or other sectors. Formal import restrictions such as tariffs applied in European Union may be found on EU TARIC Measures Information Database. However, measures such as quotas are not published and can only be tracked in a rather informal manner in articles and academic literature. Exceptionally, besides finding a formal reference for import quota implementation in Spain, for other European countries I examined the natural gas import data from Eurostat for each country separately in the aim of finding an indication for a quota level. I also used the HHI values whether there is a specific value that the respective country seeks to hold its HHI value below. I presume the HHI of Portugal's natural gas import market signals to an import quota implementation which I discuss in Section 2.3. Figure 19 and Figure 20 illustrate the suppliers' share in Portugal's natural gas import market and the corresponding HHI.

Figure 13. U.S. market share in China's coal import market



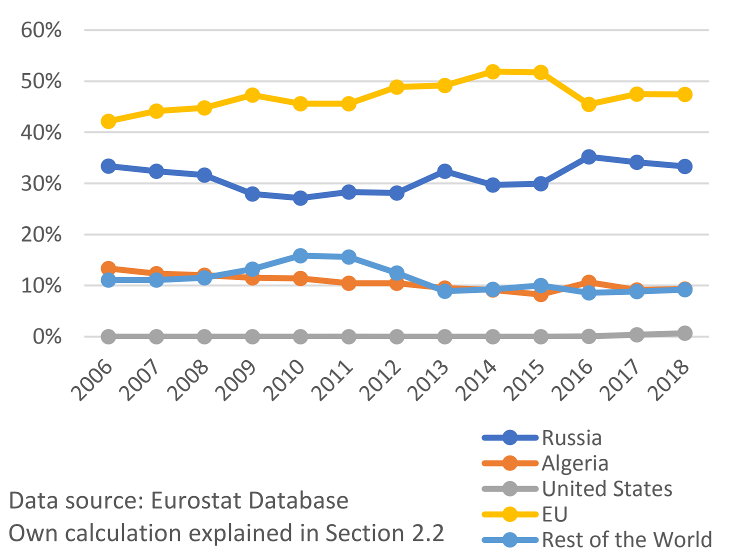
Data Source: UN COMTRADE Database modified based on EIA Database
Own calculation explained in Section 2.2

Figure 14. U.S. steam coal export prices



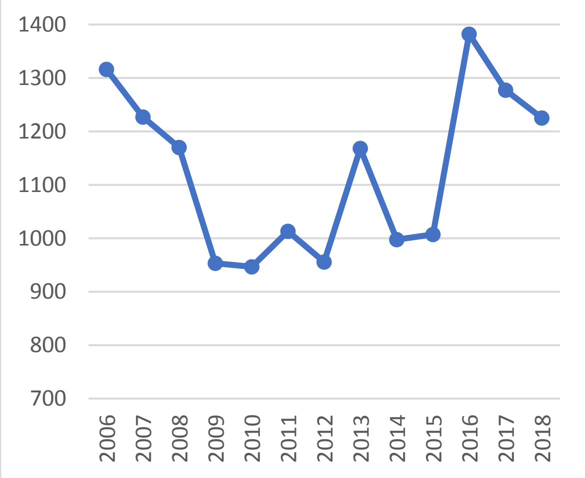
Data Source: EIA Database, BP Report (2019)

Figure 15. Market share of natural gas exporters to Europe



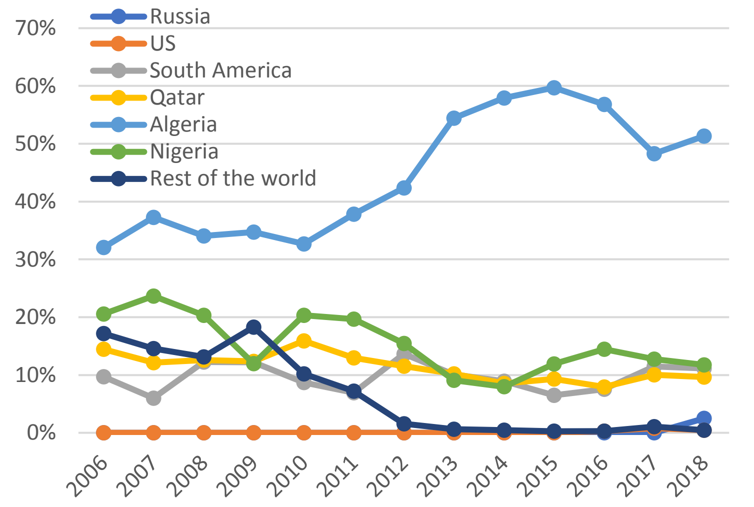
Data source: Eurostat Database
Own calculation explained in Section 2.2

Figure 16. HHI of Europe's natural gas import market



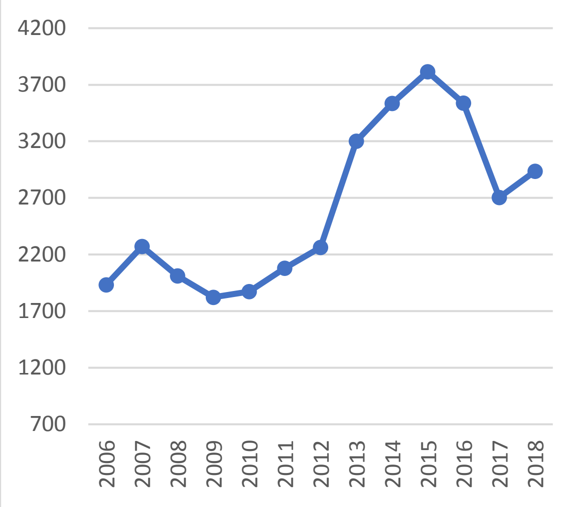
Data source: Eurostat Database
Own calculation explained in Section 2.2

Figure 17. Market share of natural gas exporters to Spain



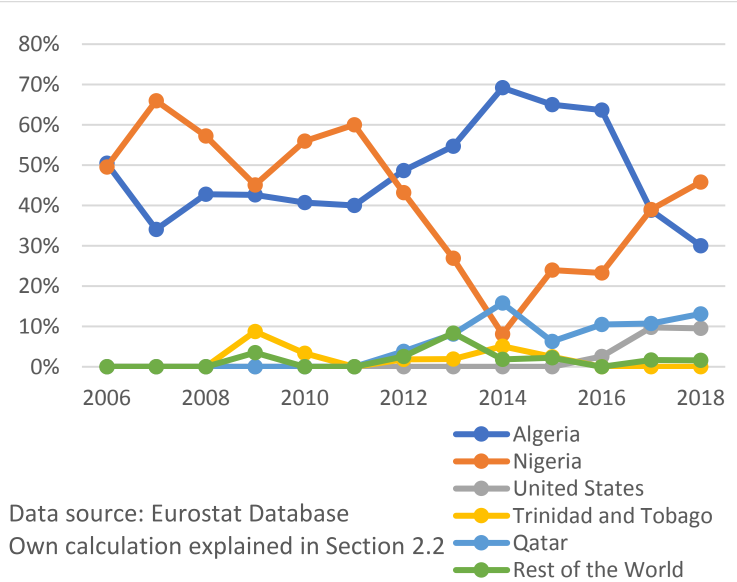
Data source: Eurostat Database
Own calculation explained in Section 2.2

Figure 18. HHI of Spain's natural gas import market



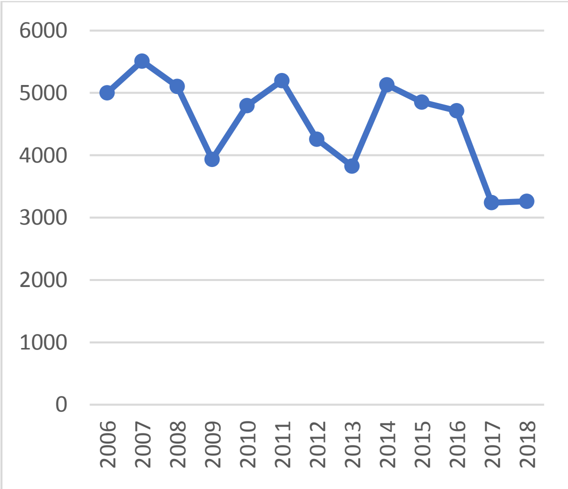
Data source: Eurostat Database
Own calculation explained in Section 2.2

Figure 19. Market share of natural gas exporters to Portugal



Data source: Eurostat Database
Own calculation explained in Section 2.2

Figure 20. HHI of Portugal's natural gas import market



Data source: Eurostat Database
Own calculation explained in Section 2.2

2.2 Preliminary Data Analysis

In this section, I explain my approach to handling with the empirical data presented in Section 2.1. Three types of empirical data have been modified and calculated during this paper: first, data on the U.S. energy mix to represent the substitution away from coal towards natural gas in the U.S. energy sector (Figure 3), second, data on the coal and natural gas trade as market percentages to track the trade flow and to show the diversification of the supply (Figure 9, 11, 13, 15, 17, 19), and third, HHI of the corresponding import market as an indicator for the security of supply (Figure 12, 16, 18, 20).

Figure 3 gives the coal and natural gas consumption in the U.S. power sector to depict the direct interplay between coal and natural gas consumption. Therefore, I neglected the contribution from the other fuel types and constructed the shares of coal and natural gas, each, under only their energy contribution taken into account in total for the period 2001-2019.

Figure 9 gives the shares of the importers in the U.S. coal export market to illustrate the changes in the U.S. coal consuming regions throughout the period 2000-2018. I expect to observe a change in the trade pattern after the Shale Gas Revolution – specifically after the year 2007. The bilateral trade parts have been neglected as the importers included in the data are historically major consumers of the U.S. coal.

Figure 11 depicts the shares of China's coal suppliers. The bilateral trade flows are taken into account, which means the coal export value of China is subtracted from the coal import value with the corresponding trade partner. The significant trade partners are selected with the following approach: I took the average of suppliers' market shares separately for the time period 2001-2018 and assumed that the countries with a market share larger than 0.1% on average are significant suppliers. These countries are (in descending order): Australia, Indonesia, Russia, Mongolia, Vietnam, Canada and the U.S. followed by New Zealand, Democratic Republic of Korea and South Africa, Colombia. I selected Australia, Indonesia, Russia and the U.S. for the illustration and combined the rest of the suppliers to the Rest of the World. In the data illustration, I combined the market shares of Australia and Indonesia, as these markets are the largest coal exporters to China and it is unnecessary to distinguish between them for this paper's scope. I calculated the shares of the suppliers as a percentage as a ratio of the net coal import value with the trade partner to China's annual coal import value. It is worth to mention that prior to 2009, China has been a net coal exporter. However, when the total coal import and export flows are examined, China historically imported from Australia, Indonesia, Russia and Mongolia and sold to the rest of the world in the period of 2001-2008 as a net coal exporter (Figure 11). Due to the logical inconsistency on the U.S.-China coal trade data in year 2015, I modified the UN COMTRADE data for 2014 and the subsequent years with the following approach: I calculated the percentage change in the coal flow from the U.S. to China and applied it on the UN COMTRADE data that gives the net coal import of China from the United States.

HHI is used as an indicator for the diversification of China's coal import market (Figure 12). After the bilateral trade has taken into account, each net export value of China in the data for Figure 11 has been set to zero since HHI serves as a security of supply (SoS) indicator. HHI value gives the dispersity of the supply, thus a low HHI value indicates a higher dispersity and a higher degree of SoS. HHI has been calculated as follows:

$$HHI = \sum_i \left(\frac{Net\ Import\ Value}{Total\ Import\ Value}\right)^2,$$

the index i denotes the 10 major suppliers which cover at least 92% and at most 99,6% of the total net import share varying with trade year and the Rest of the World given to cover the rest of the net coal import value.

Figure 15 depicts the market shares of the natural gas suppliers to European region which is as defined in this paper as consisting of EU-28, Norway and Switzerland. The market shares of the natural gas suppliers to this region are calculated as the ratio of the respective import volume with the trade partner to the sum of the total trade volume of each country included the trade executed within the European region countries. Figure 16 gives the HHI of European natural gas supply both by pipeline and LNG. The natural gas volume traded between the European countries have been neglected in the calculation of HHI and only the supply from non-European region countries are considered. The supply from European region countries should be perceived as supply with self-sufficiency at meeting own energy demand. Figure 17 and Figure 19 that depict the natural gas import market of Spain and Portugal, respectively, have been calculated with the same approach of European import market (Figure 15). The HHI values of Spain's and Portugal's natural gas import markets (Figure 18, Figure 20) are handled with the same approach as in European market.

2.3 Empirical Observation

This paper aims to address two questions regarding carbon leakage: first, whether the economic system of the coal-to-gas substitution decelerates the leakage in a global trade system where the large economies such as the U.S., Europe and China are able to switch between coal and natural gas energies, and second, whether an implementation of an import quota on coal by a large economy strengthens coal-gas-switching and thus further consolidates the decelerating effect on the CO2 emission increase induced by the coal-gas substitution.

In this section, I describe and interpret the empirical data with the background of references from the historical incidences in the aim of addressing this study's questions of interest. I discuss to what extent the data is explicable given the references on the developments in the energy markets. I discuss the data that shows the possible effects of the Shale Gas Revolution in the U.S. and on the global coal and natural gas markets, which are expected to exhibit itself as changes in the prices, import and export quantities. Further I seek to develop an intuition for how the trade mechanism works.

The aim of this section is to establish an understanding basis for the global coal and natural gas trade. Then, I include the notion of a trade barrier implementation into this intuitive framework by empirically exemplifying from the relatively explicitly-documented case of European quota on gas imports from Russian due to the security of supply reason. Further, I present the formally implemented import quota in the Spanish natural gas import market and presumably an informal one in Portugal's gas import market. Subsequently, I return back to the coal trade between the U.S. and China in order to examine whether an evidence for a trade restriction and its possible consequences are tractable in the empirical data.

2.3.1 U.S. Energy Market

The United States has expanded its natural gas production consistently with the rise in reserve discoveries. Figure 1 shows the continuous production growth. The U.S. shale gas production in 2007 rose from 1.293 bcm to 11.415 bcm in 2013 and further continued to grow by 93% in 2018 from 2013 level.

In alignment with the rising domestic gas production, the net import volume of the U.S. has decreased continuously. Figure 2 shows the net natural gas import of the U.S. by year. Prior to 2007, the U.S. has net-imported gas at a relatively constant level approximately around 350.000 MMcf. Till 2013, the net gas import fell by 65% from 2007 level and continued to decrease drastically. The U.S. became a net natural gas exporter in 2017 and exported 6.17% of its domestic consumption in 2019. This signifies that the expansion of domestic gas production satisfied the domestic demand and decreased the demand for gas imports.

Coal has been the dominant fuel in the electricity generation. This has led to excessive CO2 emission increase and as a result to the climate change problem. Global warming has been a growing concern globally since early 1990s. To tackle with the climate change problem, Kyoto Protocol (2005) and Paris Agreement (2016) have been established and put in place under UNFCCC. The U.S. has not committed to Kyoto protocol, however various U.S. administrations have set measures to deal with the climate problem. Bush administration aimed to achieve a reduction in GHG emission by subsiding the businesses that use renewable energy sources with a tax credit. Climate change measures in the U.S. have intensified in Barack Obama's Administration putting emphasis on renewable energy and less reliance on fossil fuels. In 2009, the cap-and-trade system called "Regional Greenhouse Gas Initiative" has been introduced, which is included the participation of 10 states.[3] Nevertheless, with such administrative actions taken, a significant change in the coal consumption in the U.S. energy mix until 2007 is not observable (Figure 3). Nonetheless, as the shale gas production has accelerated drastically since 2008, a substantial and continual growth in natural gas share in the power sector is evident. In the early 2000s, the share of natural gas was only making roughly 25% of the total generation from coal and gas. This relative share has been increasing persistently until 2012 and decreased in 2013 and stayed stable in 2014. The reason behind this fall in natural gas share requires further questioning. In year 2015, for the first time the share of natural gas equals to coal and a year later takes over of coal share by 3%. Until then, the share of natural gas has kept growing and replaced the coal in the U.S. power sector. The reason for the substitution of coal by natural gas may lie in the relative price changes. Whether the replacement of coal by gas in the U.S. domestic market will continue depends on the future developments in the domestic and global energy markets that affect the prevailing prices for the U.S consumers.

I take a look at the coal consumption, production and net export volume of the U.S. given in Figure 4 to observe how the domestic coal market changes as the natural gas consumption grows caused by the increasing production. The reduction in the coal consumption is observable along with a consistent decrease in production since 2008 till 2016. I have no knowledge about the reason behind the sharp decrease in production in the year 2016. The reason may be the strong decline in the coal demand both in domestic and global market.

[3] Wikipedia. Climate change policy of the United States. Retrieved from: https://en.wikipedia.org/wiki/Climate_change_policy_of_the_United_States

The U.S. coal consumption fell continuously since 2008. It can be seen that during the period 2010-2012 the consumption fell more sharply than the production. This is the period, where the U.S. net coal export volume has grown drastically, especially in year 2011. The U.S. coal net exports rose by 220% in 2012 from 2009 level. Then, it started to decline until it reached its 2008 level in year 2016. In 2015 and 2016, the global coal demand diminished due to environmental reasons and trade limitation, which will be discussed further in this section. The coal net exports started to increase again after 2016 and grew by 118% in the following two years.

European region has been a major U.S. coal consumer since the early 2000s with a market share varying between 29% and 47% (Figure 9). It can be seen that Europe strongly increased its share from U.S. coal during 2010-2012, and held at a relatively constant level in the next two years. Then, Europe lowered the coal purchase from the U.S. drastically since 2014. Prior to 2009, China as a net coal exporter has not imported coal from the U.S. With its rapid economic growth since 2000s, China became a net coal importer. It can be clearly seen that China increased coal imports from the U.S. starting from 2009 till 2015, which reached 8% of the U.S. export share in 2012.

It can be concluded that as a result of Shale Gas Boom, the U.S. coal has leaked into China and Europe during 2009-2013 while the share of the Rest of the World has dropped significantly. Along with the continual decrease in Europe's share since 2014, China has reduced its share to ca. 0% in 2015, then increased it in the two following years to 2.5% and reduced to roughly 2% in 2018. In the period 2016-2018, Europe gave strong signal for a decline in the U.S. coal demand, whereas the demand from China and the Rest of the World has stagnated similarly. Nonetheless, Indian share shows a continual growth since 2013. The U.S. has increased the coal export to India from 8% in 2016 to 15% in 2018. It can be induced that overall European and Chinese purchase of the U.S. coal are expected not to grow, while the demand from India has been replacing the lost share from Europe and China in the last years.

Briefly after examining the U.S. coal and natural gas markets, it can be concluded that as a result of the Shale Gas Revolution, the U.S. has replaced coal by natural gas in its domestic market, levelled off the coal production. During the period 2009-2014, the reduction in the domestic coal consumption has been greater than the decline in the production, which led to coal leakage from the U.S. mainly to China and European region.

2.3.2 Global Natural Gas Markets

Now I look at the U.S. and international natural gas prices and ponder on what the price determinants are, the extent of price differences in different regions. I further aim to explain the underlying reasons for the price differences and as for the last, whether the effects of Shale Gas Revolution are observable in the U.S. and in the international gas prices.

Natural gas price is mostly indexed with crude oil price (Brent crude oil price illustrated in Figure 6). I examine whether the prices of both commodities progress in a synchronized manner. Figure 5 illustrates Henry Hub natural gas spot market price in addition to average German import price and UK (Heren NBP Index) natural gas spot market prices. In accordance with the crude oil price, the natural gas prices in Europe increased in 2001 whereas Henry Hub price declined in 2001 from 2000 level. This downward price movement may be explained as a result of the so called “stock market bubble” occurred in the late 1990s in the U.S. which has emerged as the stock market downturn in 2002. Then as a result of the drastic fall in the stock market, commodity prices declined in all regions. After reaching a low at 3.33$/mil Btu, Henry Hub price made an upward spike and increased by 164% in 2005 from 2002 low and European prices rose following approximately the same trend. During this period, the crude oil price was on an upward trajectory. This increase in both commodity prices may be attributed to the so-called “2000s energy crisis” which lasted from 2003 to 2008. The reasons for this energy crisis are listed as the growing energy demand by the developing Asia especially China and various geopolitical events. Brent crude oil price was at 28.83$/bbl in 2003, which increased continually by 237% till 2008 to 97.26$/bbl. In discrepancy with the steady increase in crude oil price, the UK and the U.S. natural gas prices made a spike in 2005. There should be another underlying reason behind this price spike in 2005. The occurred two Atlantic hurricanes in year 2005 may have led to the restricted seaborne transportation and thus tightened supply of natural gas leading to a significant price increase.

In 2006, the U.S. natural gas price levelled off from its peak in 2005 and found its level on the upwards trend with a mild slope due to the growing energy demand. Then, it continued to increase again until the effect of 2007-2009 Financial Crisis become visible on the commodity and stock markets with a drastic increase in 2008 and a fall by the end of 2008. During the period 2005-2007, the average German price rose continually. I do not observe a peak at 2005, which would indicate that German natural gas market has been affected from Atlantic hurricanes. This is self-approving since Germany does not import LNG, it supplies the majority of its natural gas from Russia and European region, and therefore it is reasonable that a price shock in the average German price is not observed. However, the average German price surged by 35% while UK price increased by 6% in 2006. The gas disputes between Russia and Ukraine during 2005-2006 might have driven up the German and Eastern European gas prices.

As the result of Financial Crisis, Brent crude oil price dropped by 37% in 2009 from 2008 level on yearly average. The oil price made a huge spike after 2009 till 2011 and stayed at the same level in 2012 at ca. 111$/bbl as the global energy demand was growing rapidly after the crisis. The European natural gas prices increased in period of 2009-2011 in a synchronized way with the crude oil price. In contrast to the direct proportion between the European natural gas prices and the crude oil price, the U.S. natural gas spot price got on the clear downward trajectory and achieved a low at 2.76$ in 2012, where European natural gas prices made a high and stayed at that level. The reason behind the strong discrepancy between European prices and the U.S. price is the abundant natural gas supply in the U.S. domestic market due to the Boom. During the same period, a sharp decline in the U.S. net natural gas imports (Figure 2) and a clear shift towards natural gas in the power sector (Figure 3) are observable. This indicates that gas supply has been growing rapidly such that it decreased the need for the net imports and abundance of natural gas in the domestic market has lowered the domestic U.S. gas price so that consumption pattern changed towards natural gas.

The growth in global energy demand started to stagnate after the year 2011 as the result of the slowdown in global economic growth especially in the developing Asia. The crude oil price dropped slightly starting from 2012 till 2014 and plummeted drastically in 2015 and continued to fall subduedly making a low at 43.74$/bbl in 2016. This resulted in a fall by 61% in 2016 from the peak in 2011. The lower fossil fuel demand in Europe as a result of the move towards renewable energies have contributed to the fall in oil price in 2015. Germany has revised Renewable Energy Sources Act (EEG) in 2014 and stated a transition to an auction system from the feed-in-tariff system[4] in order to maintain the contribution of the renewable energies in the power generation on a more competitive and sustainable basis. The slowdown in global energy demand and move towards renewable energies in Europe gave a strong signal for diminishing demand in the fossil fuel market.

The following oil price decline in 2016 stems from the supply glut which is caused by the increased shale oil production in the U.S. and OPEC countries. OPEC as a swing producer did not cut down the production despite the acknowledgment of the reduced international demand in order to compete with the U.S. shale oil. The European natural gas prices followed the crude oil price and fell in the same period of 2012-2016 by ca. 54% and the UK gas price reached the same low point of 2009 crisis.

The U.S. natural gas followed a divergent price development. After the low in 2012 due to abundant supply in the domestic market, Henry Hub price increased till 2014 by 58% while the oil and European natural gas prices during the period 2013-2016 were on a strong downward trajectory. I cannot explain the reason why the U.S. natural gas price rose during 2013-2014. In the same period, share of natural gas in the U.S. energy market fell by 3%.

Henry Hub price fell in 2015 by 40% from 2014 high and stayed in the relatively same level in 2016, while European prices dropped by 30% in the same year in alignment with crude oil price. This indicates that the U.S. natural gas price is not directly indexed with crude oil as the U.S. became a significant natural gas producer. Therefore, the U.S. natural gas price moved relatively independent from crude oil compared to European gas prices. European prices got affected directly from oil price shock in 2015-2016, while the U.S. price has remained stable.

From 2016 to 2018, the crude oil price increased significantly by 64%, which has been reflected in the German natural gas market as a price increase of 46% and in the UK price an increase by 74%. I surmise that European natural gas prices show overall in the period of 2000-2018 a strong correlation to the crude oil price. The reason might lie in the fact that Europe as a net natural gas importer is a price-taker and contracts are directly indexed with crude oil price. My assumption of that U.S. gas price is not indexed with crude oil has been confirmed.[5] They stated that natural gas prices are breaking free from oil price indexation with increasing gas hubs and liquidity. They added the gas markets in the U.S. and Europe have matured allowing enough liquidity for competitive trading.

The price on Henry Hub increased only by 27% in 2018 from 2016 level. The lesser extent of the price increase compared to European prices arises from the abundant domestic production and supply in the U.S. domestic market. In 2017, the U.S. became a net gas exporter. Despite the rising production and supply on the domestic and on the international

[4] Federal Ministry for Economic Affairs and Energy. Act on the Development of Renenewable Energy Sources (RES Act 2014). Retrieved from: https://www.bmwi.de/Redaktion/EN/Downloads/renewable-energy-sources-act-eeg-2014.pdf?__blob=publicationFile&v=1

[5] Shell and DRC. (2017). China's gas development strategies. p. 345

market, Henry Hub price rose. This indicates either to the growth in domestic gas demand or the less gas supply in the domestic market possibly through gas exports.

However, the status of LNG trade in Europe is not uniform. For instance, Spain has maintained a wide diversity in LNG suppliers, Germany has started to take LNG projects in the recent years. In my observation, the North-western European natural gas price is strongly correlated with crude oil price. The indexation of European natural gas with crude oil is likely to change in the future due to the increasing liquidity given the opening of new hubs and increasing global competitiveness in natural gas markets. Europe, especially Eastern European countries are putting more emphasis on increasing the diversity in their energy supply by opening new LNG terminals in the last years, which will allow them to break free from dependency on Russian energy supply to a certain degree and enable a more secure supply. They may be able to exercise more power as a consumer against Russia's dominance on European energy market. Thus, the European natural gas market may detach itself from the oil-indexation with the increased liquidity in the gas market.

Now, I take a look at how the U.S. natural gas exports have changed after the Shale Gas Boom. Japan as the world's largest LNG importer historically purchases LNG from the U.S. prior to the Boom given in Figure 10. The U.S. increases the natural gas exports to the Rest of the World during 2010-2012. In 2016, the U.S. starts to export LNG for the first time to China, Europe, and India. The U.S. LNG export price (Figure 8) has continuously increased from 6$/thousand cf in 2006 to 16$/thousand cf in 2014. It decreased in 2015 and to 4.7$/thousand cf in 2016. The three importing regions benefitted from the lower LNG prices during this two years. In 2016, the U.S. LNG sales grew by 558% and further continued to grow by 279%, 53% in 2017 and 2018 on yearly basis. Despite the growing LNG sales, the export price stayed at relatively constant level around 5$/thousand cf in 2016-2018. I see that sales to Europe grew rapidly on a continuous basis, while the sales to India grew on a slower pace and sales to China rose more than sales to Europe in 2017 but declined in 2018 by 12,5%. I expect that LNG sales to Europe and India to increase continually if the natural gas price follows its relatively low level, whereas China would not increase its LNG supply from the U.S. as it follows rather a conservative approach in energy trade with the United States. I assume Russia would seek to compete with the U.S. shale gas both in the European and Chinese import markets.

2.3.3 Global Coal Markets

Until now, I observed how the coal production and consumption in the U.S. steadily decreased, while the coal exports have expanded after the Boom. I further observed a continuous decrease in the U.S. natural gas price and an increase in the U.S. LNG export trade since 2016. Now, I take a look at the coal prices in China, North-western Europe and the U.S. (Figure 7). I aim to explain the coal price developments in these regions.
The global coal price is not directly indexed with any other commodity. Nonetheless, the oil price may have significant effect on the regions where the transportation cost makes up a large component of the marginal cost of coal such as in China.

The spot coal prices in China and North-western Europe increased slightly in 2001, while the U.S. price increased drastically, this may be explained by the tight supply due to the "...labor shortages, equipment problems, geological problems...", as stated in EIA Coal Report (2001).

The coal prices in every region made a low in 2002 as a result of the stock market downturn, which is in alignment with the decline in oil and natural gas prices. Prices recovered in 2003 and significantly increased in 2004. From 2003 to 2008 global energy demand was growing, the increasing prices in all energy commodities is directly attributed to this reason. However, the coal prices made a spike in 2004, which is not the case in natural gas and oil price. In 2003 and 2004, Australia as the largest coal exporter in the world had problems with production capacity. This incident drove the global coal price upwards. I have no explanation that would justify the spike in European and the U.S. coal price in 2004 in terms of supply and demand change. The increase in global coal price induced by the tightened coal supply from Australia might have led to an increase in the foreign prices. Interestingly, the Chinese spot price did not get affected to a large extent and undergone an increase of 35% only, where the U.S. and European prices went up by 67% on yearly average. The relatively lesser increase in Chinese price may be explained by the fact that the Chinese consumers as swing buyers adopt to price changes by lowering the purchases from the relatively expensive supplier and increasing from the relatively cheaper suppliers. Chinese coal price kept rising steadily until the spike in 2008 Financial Crisis given its growing energy demand from fast economic growth.

The North-western European coal price declined by 16% in 2005. This is the year in which European Union introduced the cap-and-trade system, which has lowered the coal consumption and the price. Then it recovered in 2006 and grew by 130% until the price low in 2009 Global Financial Crisis.

The U.S. price increased slightly in 2005 and declined drastically in the next two subsequent years, while North-western European and Chinese spot prices were on an upward trajectory. I cannot explain this downward move in the US coal price during 2006 and 2007. According to EIA (2006, US Coal Supply and Demand Review), the second mining incident in 2006 and the diminished demand for coal due to weather conditions have lowered the U.S. coal price.

The U.S. and North-western European coal prices dropped by 48% and 52% in 2009 on yearly basis. Chinese coal market got affected less and price fell only by 16%. The reason why the Chinese spot market price did not fall to as much as European and the U.S. prices may involve that Chinese government's economic stimulus program have kept the domestic demand high and thus the coal price has not returned to its 2007 low level in the aftermath of the crisis.

Prior to 2009, China was a net coal exporter. By its rapidly growing coal consumption due to its expanding energy demand, China became a net coal importer in 2009. After the low in 2009, the European and Chinese coal prices recovered rapidly and made a peak in 2011 by increasing 72% and 45% from 2009 level, while the U.S. coal spot price followed the upward move slowly with a growth of roughly 40%. This global price spike in the coal market may have been arisen from the growing energy demand after the financial crisis, especially China has increased net coal imports by 78% in 2010 and by 24% in 2011 on the yearly basis. Further, China as world's largest coal consumer have accounted for 41% of the global coal-fired generation in 2011. Europe's coal consumption grew during this period as well. I have no certain opinion on the underlying reason behind why the U.S. price did not grow with the same extent as European and Chinese prices. I assume the abundant gas supply in the domestic market have lowered the coal demand in the U.S. and thus the U.S. coal spot price has not increased as much as European and Chinese prices.

From 2011 to 2015, the coal spot prices in these three regions declined in the same manner with crude oil and natural gas prices. This decline in all energy commodity prices are induced by the diminishing global energy demand. The growing energy demand since early 2000s has led to high amounts of investment in the production. However, as the demand growth has started to decelerate after 2011, high production capacity and slower demand growth have led to the decreasing energy prices. As a result of the supply surplus, the coal prices decreased till 2015.

Besides the stagnation in global energy demand, in 2014-2015 China and Germany have made significant announcements concerning the future of the coal markets. China has announced to raise coal tariffs to 5-6% in 2014 starting to be effective from 2015[6][7] and in Europe coal phase-out has been discussed for a long time. For instance, Belgium displaced coal in its generation mix in 2016, and many other EU countries have announced coal phase-out such as Germany, France, Italy, Netherlands, and the UK. In 2015, Germany proposed a 'climate levy' policy measure to reduce CO2 emissions from the coal plants.[8] Both these developments in Europe and China have given a strictly lower demand signal to the coal markets and as a result that the coal markets is expected to shrink. In the expectation of lower coal demand, the coal producers would cut down the global coal supply in order to match supply with the low demand and avoid a major price drop. Indeed, U.S. coal production and net coal exports (Figure 4) declined continually during 2014-2015 with a drastic fall in 2016. This is the same year where the U.S. started to export LNG to Europe, China and India (Figure 10). The change in U.S. international trade pattern towards natural gas has been induced by the significant fall in U.S. LNG export price (Figure 8) during 2015-2016.

The North-western European and Chinese coal prices have slightly recovered in 2016 from the low of 2015 and continued to increase during 2017 and 2018. It is noteworthy that the U.S. spot coal price remained stable in 2016 and did not increase while coal price in other regions have recovered from the low levels. I do not have a certain knowledge about the underlying reason. The supply surplus in the U.S. domestic market which could not be exported to China and Europe given environmental policies against coal and trade restrictions may have held the coal price in the U.S. at the same level of the previous year. The U.S. coal price rose by 42% in the following two years while Chinese and European prices increased by 40% and 53%, respectively.

2.3.4 Implementation of Tariffs and Import Quotas

Before investigating the coal trade between the U.S. and China and the issue of trade limitation due to security of supply consideration, I first give examples from European Union, Spain and Portugal on import quota implementation, as these are explicitly documented.

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[6] The Coal Hub. (2019). How China uses multiple tools to keep coal imports in check [Article]. Retrieved from: https://thecoalhub.com/how-china-uses-multiple-tools-to-keep-coal-imports-in-check.html

[7] Reuters.(2014) China to again levy coal import tariffs after nearly a decade [Article]. Retrieved from: https://www.reuters.com/article/china-coal/update-2-china-to-again-levy-coal-import-tariffs-after-nearly-a-decade-idUSL3N0S41QP20141009

[8] van der Burg, L. (2017). Cutting Europe's Lifelines to coal: Tracking Subsidies in 10 countries: Germany. Overseas Development Institute. Retrieved from: https://www.odi.org/sites/odi.org.uk/files/resource-documents/11474.pdf

Then, I proceed with the examination of coal trade between China and the U.S. under the exercise of tariffs and make further implications about a possibly implemented import quota by China on the U.S. coal.

European region covers 40-50% of its total natural gas consumption with the supply from its member countries and countries which are well-connected to its transmission system such as Norway and the UK (Figure 15). The rest of its natural gas demand is imported from mainly Russia, Algeria and Qatar. Russia has the largest share in the European natural gas import market. Its share varied between 27% in 2010 and 35% in 2016. In 2016, the coverage of own demand by European region declined by 6.2%. In the same year, in order to cover for the lowered energy independency, European region has increased Russian and Algerian share by 5.2% and 2.5%, respectively. As a result, Russia's market share reached 35% and HHI of European natural gas import market (Figure 16) rose to ca. 1400 from 1000 level. In the two subsequent years, Europe has increased diversification in its natural gas supply by decreasing Russian and Algerian share and compensating it with the increased LNG imports from Nigeria, the U.S. and South America. In the LNG import market, Europe has been lowering the share of incumbent suppliers such as Qatar and Algeria since 2015 and increasing the imports from the suppliers with a lower share to maintain a more uniformly dispersed natural gas supply. It can be concluded that Europe aims to keep HHI of its natural gas supply market well below 1400.

Spain has established a legislation regarding the security of supply in 2004 by imposing an import quota. The legislation states that only up to 60% of the annual imported energy is allowed to come from a single country.[9] In Figure 17 can be seen that Algeria has the highest market share which grew from roughly 30% prior to 2011 to 60% in 2015. During the same period, HHI increased from 2000 level to 3800 (Figure 18). In the following two years, Spain has increased the diversity in its natural gas supply by decreasing the Algerian share and increasing the LNG supply from South America, the U.S., Qatar, Nigeria and European region. For the first time, Spain imported 75 MCM LNG from the U.S. in 2016 and 760 MCM in 2017 which constituted 2.2% of its total imports. Following the increased diversification, HHI dropped to 2705 from 3800 in two years. In 2018, Spain imported natural gas for the first time from Russia (in form of LNG), which totalled to 2.5% of its share and decreased the supply from the U.S. by 1.33%. Spain is the European country with the most diversified natural gas supply from 9 LNG suppliers. Undoubtedly, Spain held the import quota of 60% and rebalanced its supply profile by increasing diversification through LNG imports.

As for the last example from Europe, even though a trade limitation is not explicitly documented, the Portuguese natural gas import market (Figure 19) reveals a possible exercise of an import quota by 70%. Algeria and Nigeria being the major gas suppliers to Portugal, their shares interplayed reciprocatively. Prior to 2012, while Portugal was decreasing the larger Nigerian share, the Algerian share rose. The Nigerian share reached to 66% in 2007, Portugal sought to decrease it by replacing it with Algerian supply. In 2009, Algeria imported LNG from South America and Africa to achieve a decline in HHI from well above 5000-level to 4000. After 2012, the Algerian share in the market inclined strongly in the following two years making up to 69.2%. The convergence of import shares twice to 70% and not exceeding it indicates to the exertion of an import quota. After the peak of HHI in 2016, Portugal decreased Algerian share from 64% to roughly 30% and again increased

[9] Royal Decree on Diversification and Minimum Level of Stocks, Real Decreto 1716/2004

Nigerian share by 23%. In 2016, Portugal has started to import LNG supply from the U.S. for the first time and increased the share of Qatar. This has lowered HHI down to 3200-levels during 2017-2018.

As the purpose of this paper is to study the effect of the Shale Gas Boom on the coal and natural gas markets, I mainly focus on the changes of the U.S. share in Chinese coal import market, natural gas trade between these two countries and the corresponding market prices. I put three types of data into perspective when interpreting the coal import of China: the market shares of Chinese coal suppliers in the import market (Figure 11), the HHI of the Chinese coal import market (Figure 12) and the prices of the U.S. steam coal export to China and Chinese coal spot market (Figure 14). I look at HHI of Chinese coal import market in order to examine the dispersity of the coal supply and the prices to check the price gap between the domestic Chinese price and the import price that Chinese consumers perceive for the U.S. coal. I aim to understand how the U.S. share (Figure 13) changes in accordance with the prices and HHI as an indicator of the security of China's coal supply.

Prior to 2005, China used to levy a 6 %-tariff on the steam coal imports.[10] I observe a strong decline in the Australian and Indonesian share, while the import from the Rest of the World, mainly coal import from Canada and Vietnam has compensated for their decreased share. In 2003, the HHI of the import market was at its peak level of 3611, which was by 31% higher from the previous year's level. After the introduction of the tariff, the market shares have rebalanced and HHI declined back to the 2002 level.

In mid-2005, China has reduced the tariff on thermal coal to 3%.[11] Consequently, the share of Russian coal has increased while Australian coal share decreased. I observe a spike in the U.S. coal export price in 2005 and do not know how to interpret it. Until 2008, China exported and imported coal with the U.S. irregularly and in insignificant volumes (Figure 13). Therefore, until the year 2008 the U.S. coal export price to China does not have much informative value. China intensified the import encouraging policy and reduced the tariff further to 1% in the late 2006 and abolished the tariff in mid-2007.[12] [13] In 2008, the market share of the US coal has increased by 1.0112% from well below 0.004%, this is also the year when the U.S. shale gas production has accelerated and the net U.S. coal exports have significantly grown (Figure 4). In 2009, China became a net coal importer and imported 232% of its last coal export volume. The market share of Australian and Indonesian coal increased by 23% in total whereas Russian coal share grew by 5.3% on a yearly basis.
Starting from 2008 till 2013, the U.S. share grew drastically, which was prior to 2008 close to 0% in 2007 to almost 5% in 2012. This 5%-growth in the U.S. market share is significant because China has expanded its total net coal import volume during the period 2010-2013 by 79%, 24%, 30% and 5% year by year. Thus, roughly 5%-growth of the U.S. market share

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[10] The Coal Hub. (2019). How China uses multiple tools to keep coal imports in check [Article]. Retrieved from: https://thecoalhub.com/how-china-uses-multiple-tools-to-keep-coal-imports-in-check.html
https://www.reuters.com/article/china-coal/update-2-china-to-again-levy-coal-import-tariffs-after-nearly-a-decade-idUSL3N0S41QP20141009
[11] Chengjin Wang, César Ducruet. Transport corridors and regional balance in China: the case of coal trade and logistics. Journal of Transport Geography, Elsevier, 2014, 40, pp.3-16. ffhalshs-01069149f
[12] Chengjin Wang, César Ducruet. Transport corridors and regional balance in China: the case of coal trade and logistics. Journal of Transport Geography, Elsevier, 2014, 40, pp.3-16. ffhalshs-01069149f
[13] China Briefing. (2014). China Regulatory Brief: China-Germany trade deals, coal import tariffs, Guangdong Wage Guidelines

during this period constitutes a significant coal flow from the U.S. to China. China has not applied any import tariff from 2008 till 2015. Comparing the prevailing U.S. export and Chinese domestic prices (Figure 14), the U.S. export price to China fell below the Chinese domestic price in 2009 and stayed well below till 2015. After the Financial Crisis till 2012, the commodity prices along with coal price rose significantly given the Chinese and global demand growth. I observe that the U.S. export price to China declined in 2010, which indicates to a supply glut of U.S. coal into the Chinese import market. The widened price gap between Chinese spot price and the U.S. export price led to a major leakage of the U.S. coal to China in 2010 (Figure 13) that constituted 4.5% of China's net coal import share.

During the period of 2008-2014, the U.S. steam coal export price to China fell continuously except the year 2011. The price surge in 2011 is attributed to the expansion of coal-fired generation in China.[14] The price decline after 2011 is explained by the slowdown in global energy demand. The price gap enlarged the most in the years 2010 and 2012, which has revealed itself as the highest U.S. market share in the Chinese coal import market. In 2012, the U.S. share reached a record value of 4.82%. In year 2012, U.S. Henry Hub price (Figure 5) plummeted from 4.4$/million Btu of 2010 high to 2.8$/million Btu in 2012 thanks to the abundant production. I further observe that as the result of strongly declined natural gas price in the U.S. domestic market, the share of natural gas in the energy mix increased from 37% to 45% in a year. This indicates that alone the coal share in U.S. electricity generation declined by 8% and Figure 4 gives that the U.S. consumption of coal has decreased by 11.7% in volume while mine production decreased by 7.2% only. The supply surplus on the international market led to decreasing coal export price from the U.S. to China. As the price gap between domestic Chinese coal spot price and the U.S. coal price has widened, China increased the import from the U.S. reaching to 4.8% of its total import. Further, I observe a continual decrease in HHI (Figure 12) during 2010-2012 from 2500-3500 interval to below 2000 as China has replaced the high share of Australian and Indonesian coal in 2009 by the imports from Russia, the U.S. and Mongolia.

After 2012, China has decreased the U.S. share from 4.4% in 2013 to 1.3% in a year. In October 2014, China has announced the import tariff to be restored for thermal coal to 5-6% starting to be put into effect in 2015.[15] Indonesia was exempt from the tariff given the trade agreement made between China and ASEAN. China also obliged a quality requirement and established a directive to coal-fired power generators to reduce and limit the usage of imported coal.[16] After the tariff implementation and reduction of the coal purchase in 2015, I observe in Figure 14 that the U.S. export price perceived by the Chinese buyers has increased from 50$/short ton to ca. 500$/short ton. I do not understand why the U.S. export price to China has made a spike in 2015. The price effect of an import quota will be discussed in Section 4. As mentioned before, Chinese government have established a directive to reduce the import coal purchase. I see that Russian share declined by 1.9%, Australian and Indonesian share grew by 1.6% while tariff implementation is effective

[14] U.S. Bureau of Labor Statistics. (2013). Coal a key player in expanded U.S. energy exports. Retrieved from: https://www.bls.gov/opub/btn/volume-2/coal-a-key-player-in-expanded-us-energy-exports.htm

[15] Reuters. (2014). Update 2-China to again levy coal import tariffs after nearly a decade [Article]. Retrieved from: https://www.reuters.com/article/china-coal/update-2-china-to-again-levy-coal-import-tariffs-after-nearly-a-decade-idUSL3N0S41QP20141009

[16] The Coal Hub. (2019). How China uses multiple tools to keep coal imports in check [Article]. Retrieved from: Retrieved from: https://thecoalhub.com/how-china-uses-multiple-tools-to-keep-coal-imports-in-check.html

(Figure 11). The U.S. market share fell from 1.3% to 0.31% in 2015 and increased again to 0.92% in 2016. The significant fall of the U.S. share in 2015 indicates that there might have been an import quota applied on the U.S. coal. In 2015, HHI has reached the second-highest peak as the result of the higher dispersion of market shares induced by the import tariff and quota. The exporters which levied the tariff such as the U.S. and Russia have reduced their share, while the countries which are exempt from the tariff have replaced and increased their share.

The natural gas price in the U.S. (Figure 5) surged during 2013-2014, whereas the domestic U.S. coal price (Figure 7) did not show an increase to the same extent, which ultimately led to fall in the natural gas share in the U.S. energy mix (Figure 3). The coal prices in all regions made a low in 2015 due to the global low coal demand and price low in the U.S is attributed to the supply surplus in the domestic market due to the reduced coal exports. In the same year, the abundant shale gas in the U.S. has decreased the domestic gas price. The falling natural gas price induced the replacement of coal to a significant degree, which showed itself as the equal shares of coal and gas in the U.S. net generation mix for the first time in the history. Along with the falling domestic U.S. gas price, the U.S. LNG export price (Figure 8) fell by 70% in 2016 from the 2014 high and the U.S. natural gas export volume (Figure 10) grew by 10-times. China imported natural gas from the United States, as it became more convenient to purchase natural gas given the low import price.

In 2017, China intensified the import controls and issued import quotas to major buyers.[17] The U.S. share rose by 0.36% to 1.28% and Russian share by 2.3% amounting to 12.03%. The large price gap between the Chinese domestic market and U.S. coal export price to China (Figure 14) is larger than all years in the period of 2009-2014, however the U.S. coal has obtained a smaller market share in 2017. The decreasing U.S. LNG export price implies that Chinese buyers' willingness to purchase U.S. coal has diminished. The fact that spot coal prices in Asian and European regions have increased leads to more tendency to substitute coal by natural gas in all regions. The U.S. coal spot price stayed stable in 2017 might have been caused by from the coal oversupply in the domestic market due to the decreased coal export.

The import tariff about 5% on steam coal that has been levied by China since 2015 has been raised by 25% in 2018 on the coal imports from the United States, totalling to 31% as a retaliatory action to the U.S. tariff exercise on the goods import from China.[18] Although the U.S. coal export price decreased and the price gap enlarged in 2018 on yearly basis, the U.S. share fell by 0.3% to ca. 1%, while imports from Russia, Australia and Indonesia to China have increased. It may indicate again a lower demand for the U.S. coal as in year 2017. The HHI has closed to 3500 in 2018. The general development of HHI hints that China aims to keep HHI below 3500.

[17] The Coal Hub. (2019). How China uses multiple tools to keep coal imports in check [Article]. Retrieved from: https://thecoalhub.com/how-china-uses-multiple-tools-to-keep-coal-imports-in-check.html
[18] Retrieved from: https://www.spglobal.com/platts/en/market-insights/latest-news/metals/051519-china-to-provide-tariff-exemptions-on-us-imports-coking-coal-on-the-list

3. Analytical Model

The model aims to show the impacts of (i) the change in production capability of natural gas and (ii) import quota on coal on the global coal and natural gas markets to represent the effects of Shale Gas Boom in the U.S. and China's implementation of an import quota. The trade decisions occur based on the changes in the relative prices of coal and gas.

With the following general equilibrium model, I intend to show analytically the economic system will restrain the carbon leakage in the electricity generation sector taking into account the substitution effect between coal and natural gas. The increasing gas production and the growing LNG trade competition on the global market induce that the world coal trade will be replaced to some extent by the growing LNG trade. Although natural resource markets represent a monopolistic competition features due to its scarcity and concentration in particular countries which also provide room for profit maximization to the suppliers, the buyers also have tools to cope with the market power of supplying economies.

Further, I include import restriction constraint of a quota which is implemented vastly due to various reasons. I demonstrate that the importing countries have certain tools to cope with suppliers' market power on the monopolistic natural resource markets. Within the framework of basic international trade economics, these import limitations contribute in the limitation of carbon leakage by changing the relative price and demand for the energy goods. In case an import restriction is applied on coal trade, natural gas gets relatively cheaper. Thus, the consumption of the less carbon intensive resource, which is natural gas, gets induced and the carbon leakage would be restricted indirectly.

3.1 International Energy Market

I distinguish between exporting and importing countries. By assumption, the world is comprised of only the large economies. The U.S., Australia and Russia are the largest energy exporting countries as a result of their abundant resource endowments. I consider China and European Union as large importing economies that are able to switch between coal and natural gas given their technological capability for substitution and their close geographical proximity to gas exporting countries. I assume a representative consumer in each country and monopolistic competition on the international coal and natural gas markets.

All countries yield an utility U from energy by consuming coal, gas and oil. In the model, I neglect the distinction between different coal types and their sector-specific usage, the form of natural gas supply (via pipeline or as LNG) and other costs associated with the trade flow such as transportation cost. The energy from renewables are also neglected as it constitutes a small percentage in the energy mix, thus I only focus on the fossil fuel trade. Exporting economies produce coal and gas for the domestic use and also for the international market. Importing countries produce only coal for their own consumption and can import both coal and natural gas in the cost of international prices.

In terms of notation, I use E and I to denote the exporting and importing economy, respectively. The superscripts c, g, o denote coal, natural gas and oil. The subscripts d and f are used to denote domestic and foreign market variables.

3.2 Consumer side in the Exporting Economy

I consider a representative consumer in the exporting country *E* with Cobb-Douglas preferences. The representative consumer yields utility by consuming quantities of coal $q_d^{E,c}$, natural gas $q_d^{E,g}$ and oil $q_d^{E,o}$ which are produced domestically. The utility function is as follows:

$$U^E = (q_d^{E,c})^{\alpha_d^{E,c}} (q_d^{E,g})^{\alpha_d^{E,g}} + (q_d^{E,o})^{\alpha_d^{E,o}} \tag{1}$$

where $\alpha_d^{E,c}$, $\alpha_d^{E,g}$, $\alpha_d^{E,o}$ are the elasticity parameters representing the taste of the consumer, $\alpha_d^{E,c}, \alpha_d^{E,g}, \alpha_d^{E,o} > 0$. These parameters can also be depicted as the economy's expenditure share on each good given the nature of Cobb-Douglas utility function. The functional form of (1) can be interpreted as coal and natural gas being close substitutes, and oil as a weak substitute to coal and gas in the electricity sector. But, oil is vastly used in the transportation sector and is of major significance in the energy mixes of countries. I further restrain the model by focusing only on the coal and natural gas quantities as I aim to observe the substitution effect between these two markets. This assumption that oil is a weak substitute to coal and natural gas may change in the future by the reasons that I discuss in the last section. The utility function is re-written as follows:

$$U^E = (q_d^{E,c})^{\alpha_d^{E,c}} (q_d^{E,g})^{\alpha_d^{E,g}} \tag{1'}$$

The consumer maximizes its utility constrained by its budget for the energy sector. The budget constitutes of the value of domestic coal and gas production with the end-consumer price and the value of international coal and gas sales. The budget function of the exporting country is given by:

$$B^E = p_d^{E,c} q_d^{E,c} + p_d^{E,g} q_d^{E,g} + p_f^{E,c} q_f^{E,c} + p_f^{E,g} q_f^{E,g} = \sum_{i=c,g} p_d^{E,i} q_d^{E,i} + \sum_{i=c,g} p_f^{E,i} q_f^{E,i} \tag{2}$$

The economy produces coal and gas to sale in the domestic market with $(p_d^{E,c}, q_d^{E,c})$, $(p_d^{E,g}, q_d^{E,g})$ being the quantities and prevailing domestic prices. The economy also yields income from the sales on the foreign market, with $(p_f^{E,c}, q_f^{E,c})$, $(p_f^{E,g}, q_f^{E,g})$ being the sales quantities and the international prices for coal and gas, respectively. Each exporting country is in monopolistic competition on the international market, thus they supply with their best response while taking their competitors' output as given. The international prices $(p_f^{E,c}, p_f^{E,g})$ are determined exogenously.

Solving the budget constrained utility maximization problem with Lagrange method, the optimal demand quantities for the domestic market are given by:

$$MRS_{q_d^{E,c}}^{q_d^{E,g}} = \frac{\delta U/\delta q_d^{E,c}}{\delta U/\delta q_d^{E,g}} = \frac{\alpha_d^{E,c}}{\alpha_d^{E,g}} \frac{q_d^{E,g}}{q_d^{E,c}} = \frac{p_d^{E,c}}{p_d^{E,g}} = p_d^E \tag{3}$$

The equation shows marginal rate of substitution (MRS) being the amount of coal with which the representative consumer in *E* is indifferent with consuming one more unit of gas in terms of the utility they yield. As the elasticity parameters are held constant, the optimal consumption decision of coal and gas depends on the relative price of the goods. A decline in the gas price increases the relative price p_d^E of coal, thus induces less consumption of coal and more consumption of natural gas to obtain the same level of utility.

By inserting the consumption quantity into the budget function, I derive the demand function in relation to the budget of the economy for the domestic use of coal and gas energies in the economy:

$$q_d^{E,c} = \frac{\alpha_d^{E,c}}{\alpha_d^{E,c}+\alpha_d^{E,g}} \frac{B^E - \sum_{i=c,g} p_f^{E,i} q_f^{E,i}}{p_d^{E,c}} \tag{4}$$

$$q_d^{E,g} = \frac{\alpha_d^{E,g}}{\alpha_d^{E,c}+\alpha_d^{E,g}} \frac{B^E - \sum_{i=c,g} p_f^{E,i} q_f^{E,i}}{p_d^{E,g}} \tag{5}$$

The first terms being the parameter quotient in Equation 4 and Eq. 5 indicate the coal and gas expenditure share of the consumer, respectively.

3.3 Consumer side in the Importing Economy

Assuming a representative consumer with Cobb-Douglas preferences, an importing country yields utility from consuming coal of its domestic production and can also procure coal and gas from the international market:

$$U^I = (q_d^{I,c})^{\alpha_d^{I,c}} (q_f^{I,c})^{\alpha_f^{I,c}} (q_f^{I,g})^{\alpha_f^{I,g}} \tag{6}$$

The importer *I* has the following budget constraint consisting of the value of domestic production with domestic coal price and quantity $(p_d^{I,c}, q_d^{I,c})$ and import value for both coal and natural gas with the international prices $\left(p_f^{I,c}, p_f^{I,g}\right)$ and import quantities $\left(q_f^{I,c}, q_f^{I,g}\right)$:

$$B^I = p_d^{I,c} q_d^{I,c} + p_f^{I,c} q_f^{I,c} + p_f^{I,g} q_f^{I,g} = p_d^{I,c} q_d^{I,c} + \sum_{i=c,g} p_f^{I,i} q_f^{I,i} \tag{7}$$

Applying Lagrange method, I derive the following marginal rate of substitution equations:

$$MRS_{q_d^{I,c}}^{q_f^{I,c}} = \frac{\delta U/\delta q_d^{I,c}}{\delta U/\delta q_f^{I,c}} = \frac{\alpha_d^{I,c}}{\alpha_f^{I,c}} \frac{q_f^{I,c}}{q_d^{I,c}} = \frac{p_d^{I,c}}{p_f^{I,c}} \tag{8}$$

The above equation implies that there is an inverse relationship between the consumption of domestic coal and imported coal in the importing country *I*. A lower foreign coal price $p_f^{I,c}$ encourages the consumer of *I* to consume less of domestic coal and to procure more from the international market as the increase in the relative price of domestic coal $p_d^{I,c}/p_f^{I,c}$ induces an increase in the relative imported coal demand $q_f^{I,c}/q_d^{I,c}$. The same relation between the domestic and foreign coal applies to the imported coal and gas quantities:

$$MRS_{q_f^{I,c}}^{q_f^{I,g}} = \frac{\delta U/\delta q_f^{I,c}}{\delta U/\delta q_f^{I,g}} = \frac{\alpha_f^{I,c}}{\alpha_f^{I,g}} \frac{q_f^{I,g}}{q_f^{I,c}} = \frac{p_f^{I,c}}{p_f^{I,g}} \,. \tag{9}$$

I further obtain the demand functions for consumption variables $q_d^{I,c}, q_f^{I,c}, q_f^{I,g}$ in relation to the expenditure share, budget of the economy and its corresponding price:

$$q_d^{I,c} = \frac{\alpha_d^{I,c}}{\alpha_d^{I,c}+\alpha_f^{I,c}+\alpha_f^{I,g}} \frac{B^I}{p_d^{I,c}}\ , \tag{10}$$

$$q_f^{I,c} = \frac{\alpha_f^{I,c}}{\alpha_d^{I,c}+\alpha_f^{I,c}+\alpha_f^{I,g}} \frac{B^I}{p_f^{I,c}}\ , \tag{11}$$

$$q_f^{I,g} = \frac{\alpha_f^{I,g}}{\alpha_d^{I,c}+\alpha_f^{I,c}+\alpha_f^{I,g}} \frac{B^I}{p_f^{I,g}}\ . \tag{12}$$

3.4 Introduction of an Import Quota

An importing country may apply an import quota on the trade quantity from a particular exporting country *E*. Equation 13 gives the import quota constraint that country *I* applies on the coal imports from country *E* and limits the actual trade quantity $q_f^{E,I,c}$ to the quota quantity $(q_f^{E,I,c})^{quota}$ and below:

$$q_f^{E,I,c} \leq x\% \sum_E q_f^{E,I,c} = (q_f^{E,I,c})^{quota}, \tag{13}$$

If the quota in the amount of $x\%$ of the total import quantity from all *E* $(q_f^{E,I,c})^{quota}$ is smaller than the optimal import quantity $(q_f^{E,I,c})^*$ which is determined by the consumer's utility function under the prevailing market prices $(p_d^{I,c}, p_f^{I,c})$, it means that the import quota is binding. As shown in Equation 14, in case the quota is binding, the actual coal import quantity $q_f^{E,I,c}$ is below the optimal market clearing coal quantity $(q_f^{E,I,c})^*$.

$$q_f^{E,I,c} \leq (q_f^{E,I,c})^* = \frac{\alpha_f^{I,c}}{\alpha_f^{I,c}} \frac{p_d^{I,c}}{p_f^{I,c}} q_d^{I,c}. \tag{14}$$

When the quota is binding, it has increasing effects on the domestic coal price $p_d^{I,c}$ and decreasing effect on the exporting country's domestic coal price $p_d^{E,c}$, which will be discussed in detail in Section 3.6.3.1.

3.5 Producer side in the Exporting Economy

Exporting country *E* produces both coal and gas. In this model many large coal producers are regarded as a single representative monopolist producer in country *E*. The monopolist coal producer of the exporting country is in monopolistic competition on the world coal market with the coal producers of other exporting economies. EIA (2018) states the largest 10 coal producers in the U.S. cover 88% of the total production. This approves that in fact the coal market in the U.S. is associated with a monopolistic market. The natural gas producers in *E* are assumed to be in perfect competition in the domestic market and in monopolistic competition on the international market. This follows from the fact that there are large number of natural gas producers as gas production is associated with low investment costs. For instance, according to Wang and Xue's study (2016) the annual number of active firms increased from 15 in 2000 to 248 in 2008, which indicates due to the vast number of gas producers the natural gas market is attributed with a perfectly competitive market features.

3.5.1 Coal Producers

Coal mining market is associated with high fixed costs and diminishing returns to scale from the fact that extraction cost increases with the production quantity. The high investment cost limits the market entry and producers may exercise market power. Thus, coal mining industry is regarded as a natural monopoly. I consider a representative coal producer that extracts coal for domestic and foreign market with $(p_d^{E,c}, q_d^{E,c})$ and $(p_f^{E,c}, q_f^{E,c})$ being the corresponding domestic, foreign prices and quantities. The international price $p_f^{E,c}$ is set exogenously and the domestic inverse demand function depends on the domestic coal production quantity $q_d^{E,c}$, the domestic price of close substitutes - in this case of natural gas, $p_d^{E,g}$. Assuming linearity, the domestic inverse demand function can be written as:

$$p_d^{E,c}\left(q_d^{E,c}, p_d^{E,g}; \theta\right) = \theta_0 + \theta_1 q_d^{E,c} + \theta_2 p_d^{E,g}, \tag{15}$$

where $\theta \equiv (\theta_0, \theta_1, \theta_2)'$. An increasing domestic coal quantity $q_d^{E,c}$ lowers the domestic coal price $p_d^{E,c}$ from the law of demand, whereas an increasing price of gas $p_d^{E,g}$ induces a higher coal demand and raises its price, therefore I assume $\theta_1 < 0,\ \theta_2 > 0$. I use the same cost function approach from the study of Knittel et al. (2018) for the coal industry. The cost function is given as follows:

$$C^{E,c}\left(q_d^{E,c}, q_f^{E,c}; \gamma\right) = \beta_0 q_d^{E,c} + \beta_1 (q_d^{E,c})^{\beta_d^E} (q_f^{E,c})^{\beta_f^E}, \tag{16}$$

where $\gamma \equiv \left(\beta_0, \beta_1, \beta_d^E, \beta_f^E\right)'$. The parameters $\beta_d^E, \beta_f^E > 1$ are associated with the increasing marginal cost of extraction for domestic and foreign markets. $\delta^2 C^{E,c}/\delta(q^c)^2 > 0$ proves the diminishing returns to scale nature of the coal production. If the economy *E* does not produce to export ($q_f^{E,c} = 0$), it produces only for the domestic market $q_d^{E,c}$ at a constant marginal cost β_0. $\beta_1 > 1$ depicts that extracting for the domestic consumption makes it more costly to produce for the foreign market. The special case $\beta_1 = 1$ does not capture this feature.

As mentioned in the previous subsection, the coal supplier first produces for the domestic market $q_d^{E,c}$, then decide on the export quantity $q_f^{E,c}$. To solve the two-step problem, I adopt backward induction and proceed with the international market problem in the same nature as in the study of Knittel et al. (2018).

The profit function of the representative coal producer in *E* is given by:

$$\max \pi^{E,c} = p_d^{E,c}\left(q_d^{E,c}, p_d^{E,g}; \theta\right) q_d^{E,c} + p_f^{E,c} q_f^{E,c} - C^{E,c}\left(q_d^{E,c}, q_f^{E,c}; \gamma\right). \tag{17}$$

Assuming monopolistic competition on the international market, I apply marginal-cost pricing on the international coal price $p_f^{E,c}$. Taking the first derivative of the cost function

(16) with respect to $q_f^{E,c}$ gives the marginal cost $MC^{E,c}$ and equally the international coal price $p_f^{E,c}$:

$$p_f^{E,c} = MC^{E,c} = \frac{\delta C^{E,c}\left(q_d^{E,c}, q_f^{E,c}; \gamma\right)}{\delta q_f^{E,c}} = \beta_f^E \beta_1 (q_d^{E,c})^{\beta_d^E} (q_f^{E,c})^{\beta_f^E - 1}. \qquad (18)$$

Following the Equation 18, I derive the quantity exporting country *E* chooses to produce for the export sales:

$$q_f^{E,c} = \left(\frac{p_f^{E,c}}{\beta_1 \beta_f^E (q_d^{E,c})^{\beta_d^E}}\right)^{\frac{1}{\beta_f^E - 1}}. \qquad (19)$$

Equation 19 indicates that the representative coal producer expands its export as the international coal price increases, $\delta q_f^{E,c} / \delta\, p_f^{E,c} > 0$, and increases export quantity with a decreasing sales in the domestic market, $\delta q_f^{E,c} / \delta\, q_d^{E,c} < 0$. Each exporting country *E* supply coal in the international market with $q_f^{E,c}$. The world coal supply can be summarized as the aggregate of the foreign coal quantities:

$$p_f^{E,c} = P(Q^c) = P\left(\textstyle\sum_E q_f^{E,c}\right), \qquad (20)$$

where $E = (U.S., Australia, Russia, Others)$. The function $P(Q^c)$ is the inverse world demand function with the global coal supply Q^c as the input.

The profit maximization problem for domestic market is then given by:

$$\max \pi^{E,c} = p_d^{E,c}\left(q_d^{E,c}, p_d^{E,g}; \theta\right) q_d^{E,c} + p_f^{E,c} q_f^{E,c}(q_d^{E,c}) - C^{E,c}\left(q_d^{E,c}, q_f^{E,c}(q_d^{E,c}, p_f^{E,c}; z); \gamma\right), \quad (21)$$

where $z \equiv \left(\beta_d^E, \beta_f^E, \beta_1\right)$. Taking first derivative of (21) with respect to $q_d^{E,c}$, I obtain the following equation:

$$-\beta_0 + \theta_0 + \theta_2 p_d^{E,g} + 2\theta_1 q_d^{E,c} + \frac{\beta_d^E(\beta_1 - 1)}{-1 + \beta_f^E}\left(\frac{p_f^{E,c}}{\beta_f^E \beta_1}\right)^{\frac{\beta_f^E}{-1+\beta_f^E}} (q_d^{E,c})^{\frac{1-\beta_d^E-\beta_f^E}{-1+\beta_f^E}} = 0 \quad (22)$$

In the case of $\beta_1 = 1$, I get the following equation:

$$-\beta_0 + \theta_0 + \theta_2 p_d^{E,g} + 2\theta_1 q_d^{E,c} = 0. \qquad (23)$$

The domestic gas price is assumed to be set exogenously from coal producers' perspective, solving (22) for $q_d^{E,c}$ gives:

$$q_d^{E,c} = \frac{\beta_0 - \theta_0 - \theta_2 p_d^{E,g}}{2\theta_1}, \qquad (24)$$

Taking the first derivative of (24) with respect to $p_d^{E,g}$ gives $\delta q_d^{E,c} / \delta p_d^{E,g} = -\theta_2 / 2\theta_1 > 0$. This implies that the coal producers in *E* increase their output for the domestic market as the domestic gas price rises. This can be also explained from the domestic consumers' perspective in Equation 3. An increase in the domestic gas price reduces the demand for gas and thus increases the coal demand. The coal supplier responds to the increased coal demand by supplying more to satisfy the domestic energy demand that utilizes less natural gas due to the increased domestic gas price. Wolak (2016) calculates the estimates for cross elasticity of coal consumption with respect to gas price in Europe to 0.18. This implies that Europe substitutes between coal and gas in response to an increase in gas price. As the gas price rises by one unit, Europe increases its coal consumption by 0.18. The positive coefficient of the cross elasticity approves the finding of the model.

After calculating the optimal coal production quantities $(q_d^{E,c}, q_f^{E,c})$ for domestic and foreign markets in the model, I proceed with the outputs in the natural gas market.

3.5.2 Natural Gas Producers

In the natural gas markets of the exporting economy E, I assume perfect competition on the domestic market and monopolistic competition on the international market. I tackle with the profit maximization problem of natural gas producers in the following way. The perfect competition in the domestic market limits the market power of the gas producers. Due to many market participants in the market, they cut off their mark-up until the domestic price $p_d^{E,g}$ equals to the marginal cost of natural gas. First, they determine the export quantity since the international market allows them to extract more profits than the perfectly competitive domestic market. I again apply backwards induction for the two-step profit maximization problem and first find the domestic market output $q_d^{E,g}$ with marginal pricing and then the quantity for the international market $q_f^{E,g}$.

In the same nature with the domestic coal price, I assume linearity for the domestic natural gas price in relation to the domestic coal price $p_d^{E,c}$ and the domestic natural gas output $q_d^{E,g}$:

$$p_d^{E,g}\left(q_d^{E,g}, p_d^{E,c}; \vartheta\right) = \nu_0 + \nu_1 q_d^{E,g} + \nu_2 p_d^{E,c}, \tag{25}$$

where $\vartheta \equiv (\nu_0, \nu_1, \nu_2)'$. Clearly, an increasing gas quantity in the domestic market $q_d^{E,g}$ lowers the domestic gas price $p_d^{E,g}$, $\nu_1 < 0$, whereas an increasing domestic coal price raises the domestic gas price, $\nu_2 > 0$, since a price increase in the substitute good induces a larger demand in that good and thus induces a price increase. I use the same cost function approach as of the coal production:

$$C^{E,g}\left(q_d^{E,g}, q_f^{E,g}; o\right) = \lambda_1 (q_d^{E,g})^{\lambda^E} (q_f^{E,g})^{\lambda^E}, \tag{26}$$

where $o \equiv (\lambda_1, \lambda^E)'$. The parameter $\lambda^E < 1$ is associated with the decreasing marginal cost of gas production for the domestic and foreign markets. $\delta^2 C^{E,g}/\delta(q^g)^2 < 0$ proves the increasing returns to scale nature of the natural gas production. I assumed away the marginal cost of gas for the domestic and foreign markets are identical and given in parameter λ^E. $\lambda_1 > 1$ shows that producing for the domestic market makes it more costly to produce for the foreign market and in case $\lambda_1 = 1$, producers are no different between producing for the domestic and foreign markets in terms of occurred marginal cost.

Perfect competition in the domestic market implies that domestic price equals to the marginal cost:

$$p_d^{E,g} = MC^{E,g} = \frac{\delta C^{E,g}\left(q_d^{E,g}, q_f^{E,g}; \lambda^E\right)}{\delta q_d^{E,g}} = \lambda_1 \lambda^E (q_d^{E,g})^{\lambda^E - 1} (q_f^{E,g})^{\lambda^E}. \tag{27}$$

Solving (27) for the domestic output quantity $q_d^{E,g}$ gives:

$$q_d^{E,g} = \left(\frac{p_d^{E,g}}{\lambda_1 \lambda^E \,(q_f^{E,g})^{\lambda^E}}\right)^{\frac{1}{\lambda^E - 1}}. \tag{28}$$

Equation 28 implies that with increasing domestic gas price $p_d^{E,g}$, producers decrease their output for the domestic market $q_d^{E,g}$, $\delta q_d^{E,g}/\delta p_d^{E,g} < 0$. Also with increasing export sales $q_f^{E,g}$, producers increase their output for the domestic market due to increasing returns to scale production of natural gas, $\delta q_d^{E,g}/\delta q_f^{E,g} > 0$.

In the second step of the profit maximization problem, gas producers find the optimal output for the foreign market $q_f^{E,g}$:

$$\max \pi^{E,g} = p_d^{E,g}\left(q_d^{E,g}(q_f^{E,g}), p_d^{E,c}; \theta\right) q_d^{E,g}(q_f^{E,g}) + p_f^{E,g} q_f^{E,g} - C^{E,g}\left(q_d^{E,g}(q_f^{E,g}), q_f^{E,g}; \lambda\right) \tag{29}$$

Taking the first derivative of (29) with respect to $q_f^{E,g}$ gives the following equation:

$$\left(\frac{p_d^{E,g}}{\lambda_1\lambda^E}\right)^{\frac{1}{\lambda^E-1}} \left(\frac{-\lambda^E}{\lambda^E-1}\right) q_f^{E,g\,\frac{1-2\lambda^E}{\lambda^E-1}} \left[v_0 + 2v_1 \left(\frac{p_d^{E,g}}{\lambda_1\lambda^E}\right)^{\frac{1}{\lambda^E-1}} q_f^{E,g\,\frac{-\lambda^E}{\lambda^E-1}} + v_2 p_d^{E,c}\right] + p_f^{E,g} + \frac{\lambda^E(\lambda_1 - 1)}{\lambda^E - 1} \left(\frac{p_d^{E,g}}{\lambda_1\lambda^E}\right)^{\frac{1}{\lambda^E-1}} q_f^{E,g\,\frac{1-2\lambda^E}{\lambda^E-1}} = 0 \tag{30}$$

For the case $\lambda_1 = 1$, which implies production for domestic does not make it more costly to produce for the foreign market, I obtain from (30):

$$\left(\frac{p_d^{E,g}}{\lambda_1\lambda^E}\right)^{\frac{1}{\lambda^E-1}} \left(\frac{-\lambda^E}{\lambda^E-1}\right) q_f^{E,g\,\frac{1-2\lambda^E}{\lambda^E-1}} \left[v_0 + 2v_1 \left(\frac{p_d^{E,g}}{\lambda_1\lambda^E}\right)^{\frac{1}{\lambda^E-1}} q_f^{E,g\,\frac{-\lambda^E}{\lambda^E-1}} + v_2 p_d^{E,c}\right] + p_f^{E,g} = 0 \tag{31}$$

After moving the first two terms into the brackets, the resulting equation is as follows:

$$q_f^{E,g\,\frac{1-2\lambda^E}{\lambda^E-1}} \left[v_0 \left(\frac{p_d^{E,g}}{\lambda_1\lambda^E}\right)^{\frac{1}{\lambda^E-1}} \left(\frac{-\lambda^E}{\lambda^E-1}\right) + 2v_1 \left(\frac{p_d^{E,g}}{\lambda_1\lambda^E}\right)^{\frac{2}{\lambda^E-1}} \left(\frac{-\lambda^E}{\lambda^E-1}\right) q_f^{E,g\,\frac{-\lambda^E}{\lambda^E-1}} + v_2 p_d^{E,c} \left(\frac{p_d^{E,g}}{\lambda_1\lambda^E}\right)^{\frac{1}{\lambda^E-1}} \left(\frac{-\lambda^E}{\lambda^E-1}\right)\right] + p_f^{E,g} = 0 \tag{32}$$

Then I move the terms including $q_f^{E,g}, p_f^{E,g}$ to the right side of the equation:

$$v_0 \left(\frac{p_d^{E,g}}{\lambda_1\lambda^E}\right)^{\frac{1}{\lambda^E-1}} \left(\frac{-\lambda^E}{\lambda^E-1}\right) + v_2 p_d^{E,c} \left(\frac{p_d^{E,g}}{\lambda_1\lambda^E}\right)^{\frac{1}{\lambda^E-1}} \left(\frac{-\lambda^E}{\lambda^E-1}\right) = \frac{-p_f^{E,g}}{q_f^{E,g\,\frac{1-2\lambda^E}{\lambda^E-1}}} - 2v_1 \left(\frac{p_d^{E,g}}{\lambda_1\lambda^E}\right)^{\frac{2}{\lambda^E-1}} \left(\frac{-\lambda^E}{\lambda^E-1}\right) q_f^{E,g\,\frac{-\lambda^E}{\lambda^E-1}} \tag{33}$$

Then I rewrite $p_d^{E,g}$ as in Equation (27) and insert it in (33), after further rearranging, I obtain the following equation for the production quantity to the foreign market:

$$q_f^{E,g} = \frac{-\left[v_0\left(\frac{-\lambda^E}{\lambda^E-1}\right)q_d^{E,g} + 2v_1\left(\frac{-\lambda^E}{\lambda^E-1}\right)(q_d^{E,g})^2 + v_2 p_d^{E,c}\right]}{p_f^{E,g}} = \frac{-\left[\left(\frac{-\lambda^E}{\lambda^E-1}\right)q_d^{E,g}\left(v_0 + 2v_1 q_d^{E,g}\right) + v_2 p_d^{E,c}\right]}{p_f^{E,g}} \tag{34}$$

The foreign price of natural gas in the denominator indicates gas producers reduce their output for the international market as the gas price $p_f^{E,g}$ rises. The first derivative of (34) with respect to gas output for domestic market gives a positive outcome, $\delta q_f^{E,g}/\delta q_d^{E,g} = -\left[\left(\frac{-\lambda^E}{\lambda^E-1}\right)\left(v_0 + 4v_1 q_d^{E,g}\right)\right]/p_f^{E,g} > 0$, which implies that with increasing domestic gas use $q_d^{E,g}$, it is also more profitable to increase the production for export sales $q_f^{E,g}$. The third and last determinant variable on $q_f^{E,g}$ is the domestic coal price in *E* $p_d^{E,c}$. I further deduce from (34) by taking first derivative with respect to domestic coal price $p_d^{E,c}$. It gives that a rise in domestic coal price induces a decrease in the export quantity from *E*, $\delta q_f^{E,g}/\delta\, p_d^{E,c} = -v_2/p_f^{E,g} < 0$.

3.6 Interpretation of the Model

In this section, I describe how the international trade mechanism works within the model framework presented in Section 3. The international trade literature splits into old and new trade theory. The old trade theory suggests that the main determinant of trade is countries' comparative advantage and disadvantage induced by the differences in their resource endowments. Leamer (1984) stated endowments of immobile scarce natural resources may be a source of comparative advantage that guides international trade. Some countries are endowed with abundant natural resources, so that they can produce to satisfy their domestic energy demand and also the demand in the international market. When countries do not hold vast resource reserves, the extraction is too costly or the extraction technology is not available to the country, then they import resources to satisfy their consumption need. The new trade theory suggests that the factors such as production with increasing returns to scale, imperfect competition and differentiation in goods might be the determinants of the international trade. I argue that both the old and the new trade theory explain effective motives for different trade patterns depending on the traded good and the market structures of the trade parties.

3.6.1 Demand side in the Importing and Exporting Economies

All consumers can switch between coal and gas for the electricity generation purpose. They decide on their consumption quantity by comparing the respective prices. The consumer in the net exporting country can substitute between domestic coal $q_d^{E,c}$ and natural gas $q_d^{E,g}$ (Equation 1'), while consumers in the net importing economy switch between domestic coal $q_d^{I,c}$, imported coal $q_f^{I,c}$ and imported natural gas $q_f^{I,g}$ (Equation 6).

The national budget saved for the energy sector in the exporting economy consists of the earnings of the labour force, which is an accumulation of the domestic production value $\sum_{i=c,g} p_d^{E,i} q_d^{E,i}$ and the value of exported goods for the exporting economy $\sum_{i=c,g} p_f^{E,i} q_f^{E,i}$

(Equation 2). The national budget of the importing economy consists of the accumulation of the domestic production value $p_d^{I,c} q_d^{I,c}$ and savings to be spent on the natural resource imports $\sum_{i=c,g} p_f^{I,i} q_f^{I,i}$ (Equation 7).

The changes in the resource prices is the determinant on the consumption choices of the consumers, when the consumers' preference tastes are assumed to be fixed. Consumers in the exporting economy *E* make their decisions based on the domestic relative price of coal and natural gas taking the prices as given and they maximize their utility within their available budget (Equation 3). However, the consumer in the importing country *I* compares the domestic and international coal price (Equation 8).

The relationship between the prices and the consumption quantities is as follows: A price increase in a good makes its substitute good relatively cheaper by changing the relative price of that good. For instance, in case of the importing country *I*, Equation 8 indicates that a price increase in domestic coal increases its relative price to foreign coal $p_d^{I,c}/p_f^{I,c}$. Marginal rate of substitution of foreign coal in terms of domestic coal is given by the ratio of marginal utilities: $MRS_{d,coal}^{f,coal} = \delta MU_{d,coal}/\delta MU_{f,coal}$. MRS is also equal to the price ratio $p_d^{I,c}/p_f^{I,c}$. The increase in domestic coal price lowers the domestic quantity that consumers can buy and increases the purchasing power for the foreign coal by lowering the relative price of foreign coal. This means, the marginal utility of foreign coal in terms of domestic coal has increased, which implies consumers are more willing to substitute domestic coal by the imported coal. The same substitution effect applies on to the domestic coal and natural gas in the exporting economy (Equation 3) and coal and natural gas imports of *I* (Equation 9).

The internal prices of goods may change due to various reasons. A technological advancement may reduce the production cost, the discovery of new deposits may yield that scarce good in abundance and decrease the price as well as changes on the demand side such as preference changes due to policy regulations may alter the relative prices and thus the relative supply and demand.

In the next two subsections, I discuss what effects and implications are of a positive change in the natural gas endowment that is also associated with increasing returns to scale production and how an import quota works in this general equilibrium model.

3.6.2 Effects of a Change in Natural Gas Production Capability

Rybczynski Theorem (1955) states that an increase in a factor endowment results in an increase in the output of the good which uses that factor intensively. This also applies to the natural resource market in the same sense such that the traded commodity may be considered as a final good of two input factors: an uniform labour force and crude resource as the endowment. The increase in the endowment of a particular resource would thus lead to an increase in the output of that good.

From the new trade theory, it is known that production with increasing returns to scale may be one of the determinants of the international trade. The natural gas production is produced with increasing returns to scale, it means that the marginal cost of natural gas production decreases with the increasing production output. Taking the second derivative of the gas production cost function (Equation 26) with respect to the output quantity either domestic or foreign, $\delta^2 C^{E,g}/(q^{E,g})^2 < 0$, implies that the cost function is concave. This means that the cost of producing one extra unit of gas diminishes with the increasing output, whether for domestic use or exports, since the fixed cost of the gas production diminishes.

The decreasing marginal cost with increasing output represents a decrease in the absolute cost of natural gas. I assume that the economy utilizes fully the budget for both coal and gas production which is also called the full employment condition. Deploying another labour unit into the natural gas production yields less coal output per unit of natural gas output, not only because gas is produced with increasing returns to scale but also the decreasing returns to scale effect in coal production complements this. Thus, the opportunity cost of natural gas decreases, as more production factor is employed in the natural gas production. This can be deduced from the cost functions of coal and gas, increasing the labour employed in natural gas sector will result in an increasing proportion of natural gas output in terms of coal output. It can be concluded that due to the production features of coal and natural gas, gas production is associated with both decreasing absolute and opportunity costs.

After the change in production capability of natural gas in E, the gas producers increase their output to satisfy the domestic demand with domestic production and reduce the natural gas imports. As a further result of increasing gas production, the abundant supply of natural gas in E lowers the domestic natural gas price $p_d^{E,g}$. This implies the relative price of coal is increased and coal becomes relatively expensive. From the consumer perspective the rise in the relative coal price induces lower coal $q_d^{E,c}$ and higher natural gas $q_d^{E,g}$ demand (Equation 3). As the taste parameters $\alpha_d^{E,c}, \alpha_d^{E,g}$ and the national budget for domestic energy demand $B^E - \sum_{i=c,g} p_f^{E,i} q_f^{E,i}$ are held constant, Equations 4 and 5 give the relationship between the price and demand for coal and gas. In the perfectly competitive natural gas market of E, the producers set $q_d^{E,g}$ (Equation 28) such that the domestic gas price equals to the marginal cost $p_d^{E,g} = MC^{E,g}(q_d^g, q_f^g; \mu^E)$ (Equation 27) that reflects the total marginal cost incurred by the production for domestic and international markets. The cost function parameter $\lambda^E < 1$ indicates to the increasing returns to scale effect in gas production. Therefore, natural gas producers have tendency to increase output because it lowers the marginal cost. However, the perfectly competitive domestic market sets the domestic gas price $p_d^{E,g}$ to the decreasing marginal cost which does not allow the gas producers to cover the fixed costs. They have the opportunity to cover the fixed costs by the profits earned on the international market, which is considered to be monopolistically competitive.
A price decrease in natural gas changes the MRS of the representative consumer in the exporting economy (Equation 3). The lower relative price of natural gas increases the consumer's gas demand and lowers the coal demand. Equation 28 implies that natural gas producers increase their output for the domestic market $q_d^{E,g}$ with decreasing domestic price $p_d^{E,g}$. Further, the abundance in gas supply induces downwards inclination of the domestic gas price.

In the next step, I examine how the representative coal producer in E reacts to the decreasing natural gas price in the domestic market $p_d^{E,g}$. It first decides on the production quantity for domestic market $q_d^{E,c}$, then it determines the quantity for coal export $q_f^{E,c}$. Equation 24 gives optimal domestic coal output $q_d^{E,c}$ in relation to the domestic gas price

$p_d^{E,g}$, the cost function parameters $\theta \equiv (\theta_0, \theta_1, \theta_2)'$ (Equation 15) and constant marginal cost parameter β_0 of domestic production when coal export is $q_f^{E,c} = 0$. The only independent quantity or price variable that determines the domestic coal output is the domestic gas price. The positive sign in the first derivative of $q_d^{E,c}$ (Equation 24) with respect to $p_d^{E,g}$ indicates that the system induces the coal producer to reduce the output for the domestic market $q_d^{E,c}$ with decreasing domestic natural gas price $p_d^{E,g}$. The reduction in coal supply in the domestic market induces a price increase. Thus, the overall price increase in coal and lower gas prices in the domestic market of *E* leads to the substitution of coal by natural gas market.

As for the second step of the profit maximization problem, the international coal price is assumed to be set by the monopolistic competition on the international market. The international price is set on the global coal market through the aggregate coal supply and demand. A decrease in coal production for the domestic market $q_d^{E,c}$ induces increasing output for the international market $q_f^{E,c}$, which is found by taking the first derivative of the coal export quantity (Equation 19) with respect to $q_d^{E,c}$ is negative, $\delta q_f^{E,c} / \delta q_d^{E,c} < 0$. Thus it is concluded that a reduction in domestic coal consumption as a result of the endowment change and increasing returns to scale effect of natural gas production induces the expansion of coal exports of *E*. This constitutes the first step of carbon leakage into the world market that is determined by the economic system.

The already opened coal mines extract coal based on their prediction on the energy markets with the aim of maximizing their total profit (Equation 21). As the domestic coal demand in *E* dropped with the drastic price fall in natural gas, the coal producers would put the produced coal into the international market. Also, similar to other natural resources, the production of coal is associated with high investment costs and relatively low marginal cost of extraction. Thus, once the mine is opened, it is profitable to exploit all the deposit until the coal price is equal to the marginal cost. Although separately from the natural resource extraction model (Hotelling's rule, 1931), alone the economic perspective of profit seeking producer supports that the profit loss in the domestic market due to decreased demand needs to be compensated by the revenue from the international market.

As more coal from *E* leaks into the world market, the coal price decreases $p_f^{E,c}$ due to the abundant coal supply. Equation 11 derived from the utility function of the representative consumer in *I* implies that with a decrease in the world coal price $p_f^{I,c}$, the demand for coal on the global market grows. The consumer in *I* determines on its coal demand from the domestic and international market by comparing the corresponding prices $p_d^{I,c}, p_f^{I,c}$. Equation 8 gives the decision between domestic and foreign coal demand based on the relative coal prices. A lower international coal price $p_f^{I,c}$ increases the relative domestic coal price in *I* and importing coal becomes more favourable than consuming the domestic coal. However, this does not certainly indicate that the imported coal consumption will grow in *I* while use of domestic coal decreases. The coal market also depends on the market of its substitute good, which is natural gas.

Now, I take a look on the natural gas supply in *E*. In the first period after the change in production capability, the vast domestic natural gas production in *E* diminishes the demand for gas imports and eventually cuts it off. As a result, the abundant gas supply decreases the domestic gas price making it relatively cheaper in comparison to domestic coal (Equation 3). With the rebalanced MRS, the representative consumer in *E* increase their natural gas consumption and thus natural gas use would gradually replace coal in the exporting country. In the perfectly competitive domestic natural gas market, producers supply domestic market until the domestic gas price $p_d^{E,g}$ equals to the marginal cost of gas production $MC^{E,g}$ (Equation 27). Equation 28 gives the optimal gas production for domestic use $q_d^{E,g}$. Increasing the domestic gas output $q_d^{E,g}$ decreases the marginal cost and domestic gas price $p_d^{E,g}$. With increasing returns to scale gas production, producers have tendency to produce until MC goes to 0 as the more production lowers the marginal cost. In the model, I neglected the fixed cost of gas production. In this market setting producers make losses in the domestic market in the amount of fixed cost since $p_d^{E,g} = MC^{E,g}$. From Equation 27 can be deduced that increasing the domestic output $q_d^{E,g}$ decreases the domestic gas price $p_d^{E,g}$ whereas increasing the export output $q_f^{E,g}$ increases the domestic gas price $p_d^{E,g}$.

Producers expand their output and produce for the monopolistically competitive international market in order to cover the loss from the domestic market and to generate extra profits. Thus, with an increasing world natural gas supply, natural gas becomes relatively cheaper to the imported coal with the decrease in the world gas price $p_f^{I,g}$ (Equation 9) and the representative consumer of *I* is more willing to purchase natural gas instead of coal from the world market. This implication on natural gas leakage into the world market might be also found in the optimal natural gas production for the domestic use as given in Equation 28. An increase in domestic gas output $q_d^{E,g}$ induces a rise in the export gas output $q_f^{E,g}$, this follows from the scale effect in gas production.

To sum up, the first effects of the falling natural gas price in the exporting economy are the decrease in coal (Equation 24) and the increase in natural gas consumption in *E* (Equation 28). The secondary effects of the change in the relative consumption of coal and gas in *E* follow as the growth in coal exports from *E* (Equation 19) as the result of reduced coal consumption in the domestic market of *E.* This is the only implication which is discussed by the carbon leakage literature. Nonetheless, the economic system induces a growth in natural gas export from *E* since the production of natural gas holds increasing returns to scale effect. Equation 34 indicates that with an increase in the production for domestic market, the gas production for exports grows. The economic system induces growth in the global natural gas trade and shrinkage of the global coal market against natural gas market which becomes more competitive, liquid and associated with lower prices. It can be further concluded the abundant natural gas production allowed by the change in production capability limits the coal demand and thus the coal trade. It is likely to that the expanding natural gas market induces a scale down in the global coal market in the future. As a result, the coal-to-gas substitution and the global move towards cleaner energies give the contraction signal for the coal markets. Due to the lower coal demand, and lower coal prices some high cost producers may shut down mines and reduce future investments, which leads to the downsizing of global coal market on the long-term.

3.6.3 Effects of the Trade Barriers

In the rest of this section, I discuss the effects of trade restriction tools on the global coal and gas markets. Nations use various tools to increase their security of supply, these can be listed as follows: diversification of supply sources and transmission routes, securing long-term contracts, good relations with the suppliers and implementation of formal and informal trade restriction tools. The traditional and well-known formal policy instrument is import tariff. Besides the wide implementation of tariffs, nations also use informal measures such as import quotas to maintain the energy dependency strictly below certain levels that are set by the government.

The import tariffs may be in form of specific or ad-valorem. Specific tariffs are taxes levied as a fixed charge per unit of the imported good. Ad-valorem tariffs are levied as a fraction of the total value of the imported good. Root (2000) explains the purpose of the tariffs as the collection of revenue for the government or protection of the domestic industry. Root declares that for a total protection of the domestic industry, the tariff levied should be at least equal to the price difference between the domestic and the import price. However, the implementation of a tariff in large economies is not as effective as an import quota. Another problem with tariffs is the fact that it may lead to the retaliatory action by the counterparty. For this reason, tariff has given its place to the import quota in the recent years.

According to Ma and Lu (2011), the widely used non-tariff trade barriers are subsidies, the anti-dumping clausal in GATT (General Agreement on Tariffs and Trade) and import quotas. Governments give subsidies to the domestic producers to support the industry in form of cash disbursements, tax exemptions, etc. Anti-dumping clausal states that dumping exists when the export price of a good is less than the price available to the domestic consumers in the exporting country. Although an importing country's consumers may benefit from the dumping action by taking advantage of the lower prices, the anti-dumping clausal has been included into WTO (World Trade Organization) in order to avoid price discrimination between national markets and to maintain a fair and free global trade environment.

Import quotas are used widely due to their effectiveness and informal nature. Countries with security of supply concerns due to the high reliance on the energy imports or its hindering effects on the domestic industry are significant, they implement import quotas in order to constrain the import flow with an absolute limitation. Ma and Lu (2011) categorized three types of import quotas: unilateral quotas, multilateral quotas and tariff quotas. Tariff quotas hold certain quantity of the imported good (either in form of absolute numbers or as percentage) subject to a certain level of duty and the quantities exceeding this quota are subject to a higher duty rate. As for an absolute quantitative limitation of the import, the unilateral and multilateral quotas work most effectively by eliminating any market response caused by the price change. National governments issue licenses to some group of individuals or firms in the exact amount of the import quantity determined by the government for a specific time period.

3.6.3.1 Economics of an Import Quota

In this section, I examine the economics of an import quota and its effects on both domestic markets in the exporting and importing country as well as the international market. I assume the importing country *I* implements a quota on coal trade with *E*. For simplicity, I neglect the subscript *c* in the variables. Figure 21, 22, 23 depict the market equilibriums under autarky, free trade and trade with the quota for the importing, international and exporting economy, respectively. The exporting country has comparative advantage in the coal production by the relatively low production cost than of the importing country. The superscript a denotes the variables for the autarky setting. The production prices and quantities under autarky are given by $(p^{E,a}, q^{E,a})$ and $(p^{I,a}, q^{I,a})$ for the exporting and importing country, respectively. This implies that the domestic autarky price in the exporting country is lower than in the importing country's autarky price, $p^{E,a} < p^{I,a}$.

Figure 21.

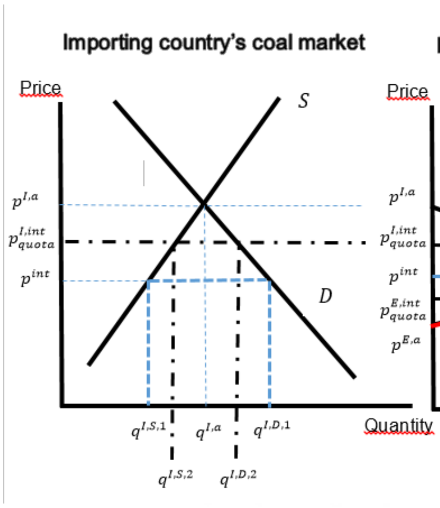


Figure 22.

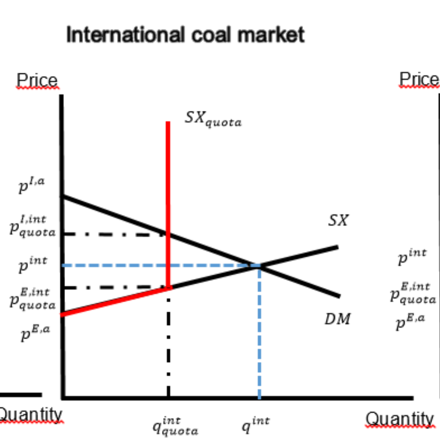
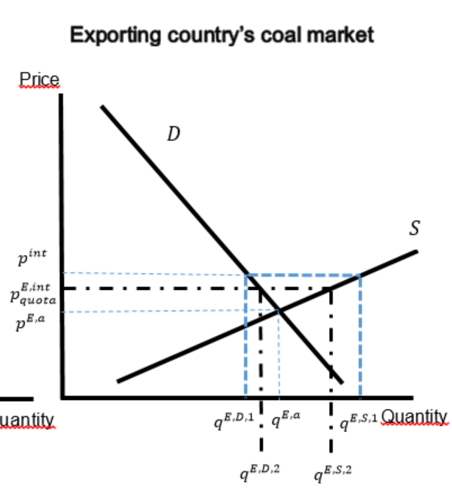


Figure 23.



Figures 21, 22, 23; Own illustration

The representative consumer in *I* has excess demand below the autarky price $p^{I,a}$ in the amount of the difference between demand and supply quantities at each price lower than the autarky price, $p^{I} < p^{I,a}$ (Figure 21). The excess demand increases with the decreasing price following the law of demand. Similarly in the exporting country, economy creates a production surplus at any market price above the autarky price $p^{E} < p^{E,a}$.

Under free trade, the importing country purchases coal from the international market if it is cheaper than its autarky price and the country with relatively lower autarky price sells coal at a higher price than its autarky price $p^{E,a}$ on the world market. Allowing the countries to trade with each other, the importing country brings its excess demand and exporting economy puts its production surplus onto the international market. The international market equilibrium is established at (p^{int}, q^{int}) by the import demand DM and export supply SX curves, which depict the excess demand of the importing and supply surplurs of the exporting economy. As shown in Figure 22, the intenational price p^{int} is smaller than the autarky price of *I* $p^{I,a}$ and larger than the autarky price of *E* $p^{E,a}$, $p^{E,a} < p^{int} < p^{I,a}$. This implies that with the new prevailing coal price in *I* has decreased and the prevailing price in *E* has increased. The superscripts 1 and 2 in the quantity variables denote the corresponding supply and demand quantities under free trade and with a quota, respectively. Now, under free trade the producers in *I* produce a quantity $q^{I,S,1}$ that is lower than the autarky output and purchase the difference between demand and supply at the international price $q^{I,D,1}$ −

$q^{I,S,1}$ from the exporting economy. Thus, the equilibrium quantity q^{int} is given as the difference between the demand and domestic supply in the importing country. On the supplier side of the international market, since the market price has increased from $p^{E,a}$ to p^{int}, producers in *E* increase the output and now produce more than the domestic demand. They produce and consume domestically with $(q^{E,S,1}, q^{E,D,1})$ and export the difference $q^{E,S,1} - q^{E,D,1}$ to *I* at the free trade equilibrium at price p^{int}.

Now, the importing country introduces a quota either as an absolute or a percentage value, as given in Equation 13. Implementation of an import quota directly restricts the coal flow from *E* to *I* to q_{quota}^{int} and thus changes the export supply curve SX to SX_{quota} as illustrated in Figure 22 as the bold curve. As the market equilibrium with the quota is reached, the price in the importing country rises until the import demand in *I* is equal to the quota level and the prevailing price in *I* equals to $p_{quota}^{I,int}$. Conversely, the market equilibrium price in the exporting country falls until export supply amounts to the quota level and equals to $p_{quota}^{E,int}$, as shown in Figures 21 and 23.

Implementation of an import quota means that the importing country *I* limits the imported quantity by $x\%$ of the market equilibrium quantity under frade q^{int} (Equation 13), thus the exporting country *E* can supply to *I* only as much as the quota volume q_{quota}^{int}. Now as a result of the higher prevailing coal price in *I*, domestic producers increase their output to $q^{I,S,2}$ due to the higher domestic price and utilize the fact that the imported coal in *I* is restricted to q_{quota}^{int}, which equals to the difference between demand and supply, $q^{I,D,2} - q^{I,S,2}$ at price $p_{quota}^{I,int}$.

3.6.3.2 Welfare Effects of an Import Quota

Figure 24 and 25 illustrate the welfare effects of an import quota on the importing and exporting country, respectively. The consumers in *I* face a higher price for both domestic and imported coal. They consume more of the domestic coal and import less due to the quota, overall they decrease their total coal consumption as a response to a higher prevailing coal price. The magnitude of the loss in consumer surplus is given by the area $-(A + B + C + D)$ in Figure 24. The area B and D are called production and consumption distortion, which represent the change in domestic production and consumption value induced by the price change. The consumers in *I* are worse-off after the implementation of an import quota. However, domestic producers in *I* profit from the higher price and sell a larger quantity. They generate more revenue compared to the free trade setting. Their extra revenue is depicted as the area $+A$ in Figure 24. As mentioned before, import quotas are implemented in order to protect the domestic industry and to maintain a higher security of supply. In case the import licenses, which amounts to the import quota q_{quota}^{int} in total, are given to the domestic producers, they buy coal from the exporting country at price $p_{quota}^{E,int}$ and sell at $p_{quota}^{I,int}$ as a result they generate a profit which amounts to $+(C + G)$, which is also called the quota rent. The quota rent is collected by the government if the quota rights are auctioned. Overall, the change in the national welfare of *I* amounts to $+G - (B + D)$. This is calculated by the sum of the consumer, producer and quota rent collectors' surplus. If the quota rights are distributed to the foreigners, then quota rents belong to the other party and the national welfare aggregates to $-(B + C + D)$.

In the exporting country, the prevailing market price decreases from p^{int} to $p_{quota}^{E,int}$ and results in a total output reduction. Consumers in *E* profit from this price decrease and increase the domestic consumption to $q^{E,D,2}$. The consumer surplus is given by the area $+e$ in Figure 25. Under free trade, producers in *E* sell their output at p^{int} and profit from their cost advantage that incurs from the price difference between their autarky price and the international price set under free trade. With the quota, they shrink their output to $q^{E,S,2}$ from $q^{E,S,1}$ and lose the surplus shown in the area $-(e+f+g+h)$.

Figure 24.

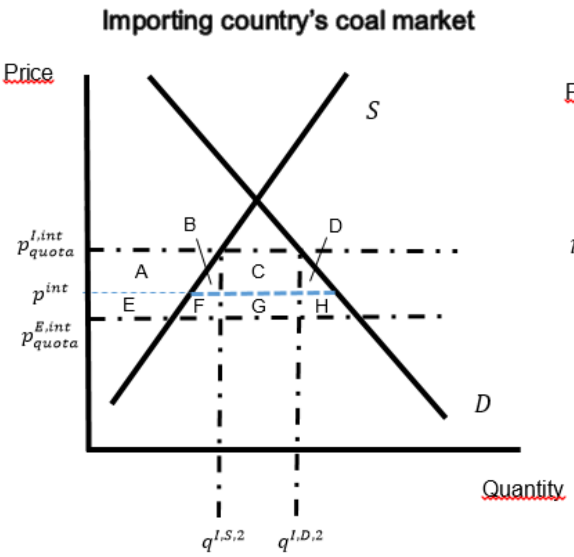
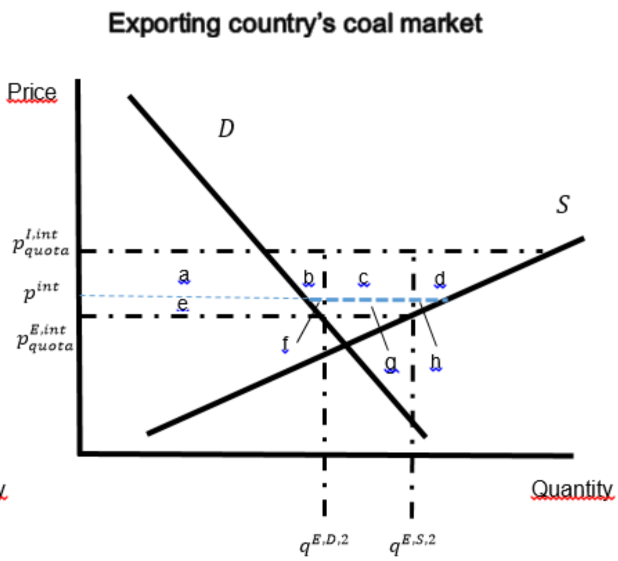


Figure 25.



Figures 24,25; Own illustration

The exporting country does not collect any quota rents unless they are distributed to them. Thus, the change in national welfare of *E* is summed up to $-(f+g+h)$. Similar to losses in importing country, the areas f and h depict the consumption and production distortion, respectively. Assuming that world consists of only these two countries, the change in world welfare is summed up to $-(B+D+f+h)$. Thus, the reduction in the world welfare is the sum of the production and consumption distortions in the importing and exporting countries (B,D), (h,f). As all these components are negative, it can be concluded that the effect of an import quota on the world welfare is negative as it reduces world production and consumption efficiency.[19]

In the rest of this section, I examine the effects of an import quota in our model setting with multiple exporters by allowing for a price discrimination between the import price and the domestic price in *I*. The import quota restricts directly the quantity that *I* can import from the exporting country *E*. The variable $p_f^{E,I,c}$ denotes the price of the restricted coal import from *E* perceived by the consumers of *I*. The restriction on the import quantity increases the import price $p_f^{E,I,c}$. The increased foreign coal price $p_f^{E,I,c}$ decreases the MRS of domestic coal in *I* and makes it relatively cheaper against the imported coal given in Equation 8. The

[19] Suranovic, S. M. (2004). International trade theory and policy. Chapter 90-14. Retrieved from: http://internationalecon.com/Trade/Tch90/T90-14.php

price gap between $p_d^{I,c}$ and $p_f^{E,I,c}$ narrows and the imported coal from country *E* loses its price advantage against the domestic coal of *I*. Assuming the consumers taste parameters are constant, the ratio of the foreign to domestic coal demand $q_f^{E,I,c}/q_d^{I,c}$ decreases. This indicates demand for the imported coal from *E* $q_f^{E,I,c}$ decreases and the demand for the domestic coal $q_d^{I,c}$ increases.

However, the restricted import quantity leads to an excess coal demand in *I* and it raises the domestic coal price $p_d^{I,c}$. I assumed the importing country *I* is a large economy. Thus, the restricted coal import from *E* to *I* has a significant effect in terms of price effect of the coal undersupply. In order to compensate for the import deficit, the importing economy raises its imports from other exporters. It is worth to mention that the restricted supply from a particular country would increase the import demand from other countries. Thus, this would also lead to a higher import price of other exporters. The raised domestic coal price in *I* due to the undersupply, in case it has not been compensated by the imports from other countries with price advantage, induces domestic producers to increase the production $q_d^{I,c}$. Through the implementation of an import quota, the domestic coal producers profit from the larger sales and higher domestic price which is in alignment with the purpose of an import quota.

As a second price effect, both increased domestic $p_d^{I,c}$ and coal price from country *E* to *I* , $p_f^{E,I,c}$ change the demand for natural gas in *I*. The importing country may substitute between the domestic, foreign coal and foreign natural gas as given in the utility function of *I* as these three fuels are close substitutes in power generation sector (Equation 6). Both increased coal prices make importing natural gas relatively cheaper and thus more attractive for consumption in *I*. The substitution effect between coal and natural gas implies that higher relative price of foreign coal to gas $p_f^{I,c}/p_f^{I,g}$ changes the relative import demand of natural coal and gas $q_f^{I,c}/q_f^{I,g}$. It increases the natural gas demand and lowers the foreign coal demand consequently, as given in Equation 9. The interplay between domestic coal and natural gas import demand depends on various factors, not only on the price changes in coal price and natural gas, but also on measures that induce coal-gas switching such as climate policies. The price increase in domestic coal due to the quota makes natural gas imports more attractive, it leads to a growth in natural gas demand $q_f^{I,g}$ and to a decrease in the domestic coal demand $q_d^{I,c}$.

The substitution between coal and natural gas counteracts the purpose of an import quota in terms of increasing the security of supply and supporting the domestic coal industry. The increased domestic coal price makes the natural gas imports more attractive, thus it takes the excess demand for domestic coal away towards natural gas imports. This has a dampening effect on the domestic coal sales and on the increase in domestic coal price, which are required to support domestic coal producers.

The increase in domestic coal price depends on to the extent of the coal imports and the natural gas imports from the international market as a means to compensate for the excess demand due to the import quota exercise. In case the country replaces the energy deficit by raising coal imports from other exporters, the domestic price may stay unchanged. But since the purpose of import quota is primarily raising the national security and the protection of the domestic industry, the consumption of the domestic coal should increase. The substitution effect between coal and natural gas dampens the aim of using an import quota.

The exporting country *E* cannot export the quantity to *I* that is normally exported under free trade. The excess supply of coal shifts partly into the domestic market of *E* and partly into the international market for other importing economies. The excess coal supply on the domestic market of *E* increases the available coal and decreases domestic coal price $p_d^{E,c}$. The profit function of the representative coal producer in *E* (Equation 17) is given as the sum of revenues from domestic market and foreign market subtracted by the cost of production. As the domestic coal price decreases, the profit from selling an extra unit of coal diminishes thanks to the decreased unit revenue and increasing marginal cost of coal production. Since producing more coal for domestic market leads to a decrease in profit, the monopolistic coal producer in *E* reduces the domestic output $q_d^{E,c}$ in order not to contribute to the production surplus in the domestic market caused by the trade barrier and to offset the price fall. The decrease in the relative coal price to natural gas changes the marginal rate of substitution (Equation 3) and decreases the relative natural gas demand $q_d^{E,g}/q_d^{E,c}$. The economic system induces a diminished natural gas and a larger coal demand in the domestic market of the exporting economy.

From gas producers' perspective, production is associated with increasing returns to scale (IRS), thus they would not decrease their output level since an increasing output decreases the marginal cost of production (Equation 27). They would raise the output for the domestic market $q_d^{E,g}$ and lower the gas price $p_d^{E,g}$. In fact, the gas producers producing with IRS in the perfectly competitive domestic market increase the output for foreign sales in order to cover the loss from the domestic market in the amount of the fixed costs. It can be concluded that the IRS nature of gas production induces the replacement of coal by gas both in the domestic and international market.

To examine the world prices, it is important to consider both demand and supply side factors. Trade barriers such as tariffs and quotas on coal as well as climate policies towards cleaner energies indicate a lower coal demand. The reduced coal demand signal leads to less investment in the mining sector, transportation ports and capacity extensions, which eventually indicate there will be less supply on the world coal market. Following the law of supply and demand, lower supply would lead to higher prices. It indicates that coal with a higher price due to scarcer supply faces natural gas on the international market, which is traded with growing competitiveness and at falling prices.

Implementation of a coal import quota by a large economy reduces the demand for coal on the international market by directly restricting the trade quantity. Further price development of coal depends on how world coal and gas markets change. However as a short term result of the reduced coal demand and already produced coal, exporters put their output on the international market. A part of the excess coal supply from *E* leaks into the international market. This induces a price decrease on the international coal market. Coal producers lower their output for the international market $q_f^{E,c}$ with the decreasing international coal price $p_f^{E,c}$ (Equation 19). The falling coal price $p_f^{E,c}$ may attract other importing economies which do not implement any trade barriers, and which are unable to substitute between coal and gas. Thus, the cheaper coal may leak into other importing regions.

As mentioned before, the implementation of an import quota has effects on both global coal and gas trade by increasing the domestic coal price and changing the substitutability between coal and natural gas in the domestic market of quota implementing economy. The importing country *I* increases its domestic coal production, however the increased domestic coal price induces the relative natural gas demand to grow against the domestic coal. Natural gas exporters in *E* which are in perfect competition in the domestic market have opportunity to yield profit from the international market. If the international gas price $p_f^{E,g}$ is above the domestic gas price $p_d^{E,g}$ which equals to the marginal cost of gas production $MC^{E,g}$ (Equation 27), natural gas producers increase their output for exports $q_f^{E,g}$. They partly satisfy the energy demand of the importing country which applied an import quota, if they have not compensated for their diminished coal imports by the domestic coal production. The increased natural gas production in *E* leads to a decreasing marginal cost as production costs fall with increasing output due to IRS nature of natural gas production. The falling marginal cost decreases the domestic natural gas price as given in Equation 27. It offsets the first effect of the import quota in the exporting country which is the decreased relative coal price and increased substitutability for coal away from natural gas.

It may be concluded that the implementation of the import quota on coal has two effects with regards to the carbon leakage. First, it alleviates the carbon leakage by directly restricting the import quantity and decreasing coal price in the exporting economy which leads to a reduced future coal supply and carbon leakage on the long-term. Secondly, natural gas is associated with falling global prices due to its increasing returns to scale production and liquidity in the global markets. This further decreases the coal demand and replaces the coal market to some extent, which also ceases the carbon leakage due its less CO2 content.

4. Empirical Data and Analytical Model

In this section, I bring together the empirical data with the analytical model and interpret the data within the economic framework presented in the model in Section 3. I aim to explain the empirical data from the economic point of view of the model and ponder on the extent of its consistency with the model.

As mentioned in the previous section, I distinguish between countries as a net importer and net exporter in coal and gas markets. To address the question of this study, I exemplify the net exporting country with the United States and net importing country with China to refer to the carbon leakage problem induced by a change in a resource endowment and the effects on an exercise of an import constraint.

China is one of the rapidly growing economies since 2000s and became a net coal importer in 2009. Its significant energy demand cannot be satisfied by the domestic coal production. The growing energy demand and transportation constraints on coal from South-east coastal regions of China caused shortages, which made importing coal more favourable. Coal price in China is associated with high transportation costs and high taxes. The relatively high cost burden on the domestic price puts coal mining sector into comparative disadvantage position. This caused a significant price gap of coal between Chinese and the international market, especially Australian and Indonesian coal. Chinese buyers have tendency to increase coal imports as the price gap enlarges and slow down the coal purchase as the price gap closes. Thus, Chinese coal buyers are swing buyers that immediately respond to the price changes. On the other hand, the U.S. has been a net coal exporter for decades and became a net natural gas exporter in 2017 by its abundant production after the Shale Gas Revolution.

The development of shale fracturing technology enabled the U.S. the utilization of vast amounts of natural gas deposits. Total proved natural gas reserves of the U.S. has increased by 104% in ten years (EIA, 2018). As the natural gas production exhibits increasing returns to scale feature, once the pipelines are installed they exploit full capacity of the deposits in order to finance the high installation costs. As shale fracturing is a new technology, I assume world's growing interest in shale gas away from coal will lead to increasing gas exploration and rising gas reserves. Thus, technological advancement will be more than an offset to the depletion effect in the energy resource in the short-term.

4.1 Replacement of Coal by Shale Gas in the U.S. Energy Market

In fact, I observe a continual growth in shale gas production in the U.S. after the year 2007 (Figure 1). Simultaneously, starting from 2008, the U.S. decreased its natural gas net imports (Figure 2). It indicates that the increasing domestic gas production has reduced the natural gas imports. Further, I observe a continual increase in natural gas share in the U.S. energy sector since 2009 (Figure 3) that illustrates the changing consumption pattern in the U.S. energy sector.

The price effect of the Boom is clearly observable in the U.S. natural gas when compared with prices in European region (Figure 5). Prior to 2008, the U.S. price followed the same trajectory with average German price and UK gas price, where in fact the U.S. gas price held on average higher prices compared to both. As the effect of the Boom started to become visible after the year 2008, the U.S. gas price broke free thanks to its abundant gas production from the conformity with European prices which are mainly tied to crude oil price.

The domestic gas demand and supply in E are given in Equation 3 after conversion to $q_d^{E,g}$ and Equation 28:

$$q_d^{E,g} = \frac{\alpha_d^{E,g}}{\alpha_d^{E,c}} \frac{p_d^{E,c}}{p_d^{E,g}} q_d^{E,c} = \left(\frac{p_d^{E,g}}{\lambda_1 \lambda^E \, (q_f^{E,g})^{\lambda^E}} \right)^{\frac{1}{\lambda^E - 1}}$$

The increasing shale gas production $q_d^{E,g}$ first decreased the domestic gas price $p_d^{E,g}$ that is given in Equation 25 as implied with the parameter $\nu_1 < 0$. This is clearly observable after 2008 with the continual decline in the gas price until the year 2013 (Figure 5). In the period 2009-2012, the downwards moving gas price and sharply increasing coal price during 2009-2011 drastically raised the relative domestic price of coal to gas $p_d^{E,c}/p_d^{E,g}$, which led to a significant relative demand growth for natural gas in the United States. The steady increase in the gas share in the U.S. generation mix (Figure 3) during 2009-2012 supports the change in consumer preference towards gas away from coal.

During the period 2009-2012, the U.S. gas price declined strongly while European prices rose. The production of shale gas in the U.S. is associated with increasing returns to scale as given in Equation 27 with the cost parameter $\mu^E < 1$. As the production output for domestic sales $q_d^{E,g}$ grew, the marginal cost of production $MC^{E,g}$ and the domestic gas price $p_d^{E,g}$ decreased.

The falling domestic gas price in the U.S. $p_d^{E,g}$ has rebalanced MRS (Equation 3) and lowered the relative domestic coal demand. The coal output for the domestic market is directly determined, as given in Equation 24, by the constant marginal cost β_0 when export production is zero, and the coal price coefficients from Equation 15. As a result of the diminished relative coal demand, the representative monopolist coal producer reduces its output for the domestic market. This can be deduced from Equation 24, the coefficient of domestic coal quantity holds a negative sign for the domestic coal price, $\theta_1 < 0$ and the gas price is in a positive correlation with the coal price as a price increase in a substitute good induces a price increase in that good, $\theta_2 > 0$. After taking the first derivative of Equation 24 with respect to gas price, it yields $-\theta_2/2\theta_1 > 0$, which implies that as the gas prices fall, the coal producer diminishes its output for the domestic market. Thus, the model confirms the substitution of coal by shale gas which has been well observed in the changing pattern of U.S. energy mix (Figure 3).

4.2 Carbon Leakage from the U.S. to China

Now I take a look at the change in coal prices to address the effect of the Boom on the U.S. coal price (Figure 7). I expect to find the U.S. coal price lower compared to European and Chinese coal prices after 2007 since the abundant gas supply and the low gas price have diminished the domestic coal demand. Prior to the Shale Gas Revolution, the U.S. coal price swung between the North-western European and Chinese coal prices. Indeed, after the year 2007 since then - with the exception of year 2008, the U.S. spot coal price remained well below the Chinese and North-western European prices. In year 2008 of Financial Crisis, the U.S. price was below North-western European and above Chinese price. It coincided with the increasing gas supply from the Boom in the domestic market, then the U.S. coal price made a strong decline and stayed below both prices after 2009 and since then. It clearly gives away the drastic change in the coal price and thus the diminishing domestic coal demand caused by the Shale Gas Revolution.

As the domestic coal demand and the production for the domestic market declined significantly due to the expansion of the shale gas production and the replacement of coal by gas, the U.S. coal producer required to increase the coal export to compensate for the profit losses in the domestic market. The determinants on the coal output for exports $q_f^{E,c}$ are the international coal price $p_f^{E,c}$, the output for the domestic market $q_d^{E,c}$ and the cost function parameters $\beta_1, \beta_d^E, \beta_f^E$ as given in Equation 19. Taking the first derivative of $q_f^{E,c}$ with respect to the production quantity for domestic market $q_d^{E,c}$ gives $\delta q_f^{E,c}/\delta\, q_d^{E,c} < 0$. This indicates that the coal producer raises its output for the export sales $q_f^{E,c}$ as the output for the domestic market $q_d^{E,c}$ falls. The empirical data on the U.S. coal exports clearly supports the model by the significant growth in the U.S coal exports after the year 2009 till the decrease in 2013 (Figure 4).

Prior to year 2009, the U.S. coal export price to China illustrated in Figure 14 fluctuated around the Chinese spot price. It fell below the Chinese price in year 2009 and stayed below it with the exception of the period 2015-2016 on yearly average basis. The lower price of the imported coal $p_f^{I,c}$ from the U.S. to China changed the MRS of China's demand side (Equation 8) by raising the relative domestic price $p_d^{I,c}/p_f^{I,c}$:

$$q_f^{I,c} = \frac{\alpha_f^{I,c}}{\alpha_d^{I,c}} \frac{p_d^{I,c}}{p_f^{I,c}} q_d^{I,c} = \sum_{\forall E} \left(\frac{p_f^{E,c}}{\beta_1 \beta_f^E (q_d^{E,c})^{\beta_d^E}} \right)^{\frac{1}{\beta_f^E - 1}}$$

This resulted in China's demand growth for the imported cheap coal. Clearly, the coal net export from the U.S. surged after 2007 till 2013 as shown in Figure 4. The leakage of the cheap U.S. coal into the international market met China's expanding coal demand for the cheap energy. The willingness of the U.S. to supply coal to China has been so high that the export price followed a downwards trajectory during 2008-2014 with the exception of the year 2011, as illustrated in Figure 14. In 2011, the global energy demand after the Financial Crisis has expanded significantly, which has reflected itself as an increase in all energy commodity prices. This significant growth in the U.S. coal export as a result of the Boom supports empirically the coal-to-gas substitution effect caused by the Shale Gas Revolution in the U.S. domestic market and the carbon leakage from the U.S. to China.

4.3 Natural Gas Leakage from the U.S. to the World

As the first main point, this paper aims to highlight is that the economic system of the international trade induces the substitution of the global coal market by the natural gas market to a certain extent. Following the coal leakage from the U.S. into the international market, especially to China during the period 2008-2012, the global economic growth has started to decelerate after the year 2011, which has led to a decreasing global energy demand growth. The announcements in 2014 on trade restriction measures by China and policy changes against coal-fired power generation in Europe drove to the strictly falling coal demand and thus the U.S. coal production and net coal exports in the two subsequent years. Global coal market has shrunk as a result of the globally diminishing coal demand. Further, India plans to level off the coal-fired generation in the country, which also implies strong demand decline for the U.S. coal as India has been a significant importer in the last decade. From the model follows that the representative monopolist coal producer in *E* (Equation 19) declines the output for the international market $q_f^{E,c}$ with the expectation of a lower international coal price $p_f^{E,c}$ due to the lower global coal demand. The expectation of a low coal demand also applies to the domestic market in *E.* Thus, both lower coal supply in the domestic and international markets contribute to the rising coal prices which makes it less price competitive against natural gas which is tied with falling prices. As the coal production is associated with decreasing returns to scale, the levelling-off in the coal sector creates a significant financing and investment problem since the coal producers face problems with the financing of already opened mines and the drastically dropped profits do not attract new investments. During the period 2012-2015, a consistent downward movement of coal prices in all regions (Figure 7) is clearly observable due to the diminishing demand along with the declining coal production in the U.S. (Figure 4). After the coal production have declined as a response to the measures taken during 2014-2016, the shrunken global coal supply led to the rising prices since then as illustrated in Figure 7.

On the other hand, I take a look at the production side of the natural gas market to understand how the interplay between these two markets proceeds. The cost function of gas production which is associated with increasing returns to scale (IRS) feature implies that (Equation 27) increasing the output for domestic market $q_d^{E,g}$ decreases the marginal cost $MC^{E,g}$ and thus the domestic gas price $p_d^{E,g}$, while increasing the export quantity increases the marginal cost $MC^{E,g}$ and the domestic gas price $p_d^{E,g}$. The gas producers in E increase their export quantity in order to offset the price decline in the domestic market and increase their profit to compensate for the fixed costs since the revenue from the domestic market covers only the marginal cost of production. This can be concluded also from Equation 34 for the gas export quantity $q_f^{E,g}$. Increasing the output for the domestic market $q_d^{E,g}$ induces an increase in the gas export quantity $q_f^{E,g}$. Thanks to the growth in exploration and opening of new wells, the natural gas production in the U.S. has been increasing steadily (Figure 1). The expanding gas production led to the abundance of gas supply in the U.S. domestic market $q_d^{E,g}$, which ultimately decreased continually the domestic price during the period 2009-2016 with the exception of an upwards price movement during 2013-2014 (Figure 5). The substitution of coal by shale gas in the U.S. power generation is clearly to observe in Figure 3 during the same period and accelerated in the following years.

In years 2013 and 2014, an increase of the coal use in the energy sector is observed contrary to the previous years. The decline in the U.S. coal production continued in 2013 and stopped in 2014, while the net U.S. coal export volume has started to decline in 2013 and in the following years. In 2013, the shale gas production has not increased with the same extent of the previous years. The lower supply of shale gas in the domestic market have induced a rise in gas price, as it can be seen in Figure 5. The relatively higher price of natural gas and relatively stable levels of coal price changed the U.S. MRS of coal to gas by lowering the relative price of coal (Equation 3). Thus, the representative U.S. consumer is inclined to substitute gas by coal. Indeed, the share of coal in the power generation sector has increased in 2013 by 3% and stayed at the same level in 2014 (Figure 3). As Henry Hub price declined in 2015 back to 2012 low, the share of coal and natural gas has been equal in the U.S. power generation for the first time and increased by 3% in 2016. This implies that gas supply has been such in abundance so that the domestic market got saturated. It is followed by the fact that U.S. cut off importing natural gas and became a net gas exporter in year 2017.

The saturation in the domestic market forced the gas producers to increase output for the export sales. From Equation 34 follows that perfectly competitive gas producers in the domestic market increase their output for the international market as their output for the domestic market increases. Given the continual increase in the natural gas supply (Figure 1) and the U.S. market saturation with gas in 2015-2016, the gas producers sought to satisfy the international demand. The export price of U.S. LNG declined drastically during 2015-2016 by 70% from 2014 level as it can be seen in Figure 8. As a result of the lowered U.S. LNG export price coupled with the diminished global coal demand during the same period, the importing economies perceived a lower relative price for the imported natural gas. This has rebalanced their MRS (Equation 9) of the imported coal to gas. Indeed, the U.S. has exported natural gas for the first time to Europe, China and India in 2016 (Figure 10). It is worth to mention that India as a swing buyer has not increased its coal purchase from the U.S. in 2016 from the previous year level. However, it procured LNG from the U.S. in 2016 as the export price made a drastic fall. Despite the abundant gas supply in the domestic market in 2016, which reflected itself as higher gas share in the U.S. energy sector, a slight decline in Henry Hub price is observable while European gas prices fell significantly due to the oil-indexation (Figure 5). The growing gas exports from the U.S. might have reduced the gas quantity in the domestic market and thus offset the continual decline in the domestic gas price.

The shale gas production (Figure 1) continued to grow in the following two years and the U.S. became a net gas exporter in 2017 (Figure 2). The expanding global LNG demand and the domestic shale gas demand in the U.S. are reflected in the rising natural gas spot prices (Figure 5) in all regions. As the U.S. domestic market got saturated with natural gas due to the expanding gas production, the U.S. sought to increase LNG export at lower prices than of the previous year in 2017. Thus, the U.S LNG leaked into the international market historically at the lowest prices (Figure 8). In the same year, the U.S. domestic gas price rose by 20% as shown in Figure 5.

The lower global coal demand led to the declining U.S. coal production until 2017 (Figure 4). After the oil supply glut in 2016, the global energy demand started to grow again in 2017. Due to the shrunken global coal production, the coal prices in all regions got on an upwards trend as depicted in Figure 7. The rising coal prices and low U.S. LNG export price have further widened the price difference between coal and natural gas for the importing economies. The marginal rate of substitution of coal imports for imported gas has increased (Equation 9) and thus it has become more favourable to import natural gas instead of coal as a result of the price changes. Indeed, the LNG exports of the U.S. to China and Europe have surged and satisfied their energy demand that has been unmet due to the reduced coal consumption. The expanded LNG exports, which are denoted as $q_f^{E,g}$ in the model, have increased the marginal cost $MC^{E,g}$ and the domestic gas price $p_d^{E,g}$ (Equation 27). As implied before, increasing the export quantity increases the marginal cost and the domestic price, $\delta p_d^{E,g} / \delta\, q_f^{E,g} > 0$. A price increase in the U.S. domestic gas price is indeed observable in year 2017 (Figure 5) despite the growing shale gas production. The gas consumption in the U.S. energy sector has declined by 1%, which might be attributable to the increase in the domestic price.

In year 2018, the coal production in the U.S. (Figure 4) have declined due to the continual fall in both domestic and international demand, while the net coal export has increased in volume. However, only the share of India in the U.S. coal exports has increased, where European and Chinese share showed a strong decline in the U.S. coal exports. This indicates to the continuing demand decline for coal in European region and in China. The global upwards trend of spot coal prices due to scale down in the production implies that coal will be less consumed and thus the demand for cheap natural gas will grow. The diminishing demand for coal contributes to the investment problems and leads to shrinkage of coal sector globally.

The U.S. LNG export price has increased by 11% in 2018 on yearly basis (Figure 8) despite the abundant U.S. LNG supply on the international market. The export price in the denominator in Equation 34 indicates that gas producers increase the output $q_f^{E,g}$ with falling export price $p_f^{E,g}$. It is in alignment with the model in a sense that the U.S. LNG export sales have continued to expand in 2018 with an insignificant price increase. It is possible that the growth in LNG export of the U.S. is induced by the growing competitiveness on the international LNG market. This indicates to the growing global LNG demand so that the increase in the export price has not raised the relative price of the imported gas for the importing countries significantly such that it would change the purchasing preference by changing their marginal rate of substitution:

$$MRS_{q_f^{I,c}}^{q_f^{I,g}} = \frac{\delta U/\delta q_f^{I,c}}{\delta U/\delta q_f^{I,g}} < \frac{p_f^{I,c}}{p_f^{I,g}}.$$

Further, with increasing export sales $q_f^{E,g}$, the gas producers increase their output for the domestic market $q_d^{E,g}$ following the feature of scale effect in production, as given in Equation 28. This reduces the marginal cost and domestic market price $p_d^{E,g}$. Aside from the trade economics, the reduction in the domestic price is also constrained with the marginal cost occurring from the physical production. I see that the Henry Hub price (Figure 5) increased only by 5% that is not significant. This can be explained by the growing domestic gas demand in the United States. Despite the price increase, the U.S. has increased the natural gas share in the energy sector by 4%, which is substantial in terms of share in energy mix. The growth of gas share despite the price increase indicates that the relative price of gas to coal in the U.S. domestic market is lower than its relative utility. It is noteworthy that the strong rise in coal price is one of the factors that contributed to the significant growth of natural gas share in year 2018 by increasing the relative coal price (Equation 3) and thus induced a higher consumption of the relatively cheaper natural gas.

4.4 Effects of China's Trade Barriers due to Security of Supply Reason

Now, I take a look at the coal trade between China and the U.S. after the Shale Gas Revolution (Figure 13). Prior to the year 2008 – before China became a net coal importer, China imported and exported with the U.S. inconsistently. In reality it applies for a swing buyer that the larger the price gap between the domestic price and the import price, the more quantity is traded. Following this logic, Figure 14 shows that the price gap has widened most in years 2010 and 2012, which is in alignment with the fact that the U.S. reached its record shares in the Chinese coal import market in those years. Starting from 2008 till 2015, China's coal imports from the U.S. rose drastically which is referred as the carbon leakage from the U.S. as a result of the Shale Gas Revolution. The U.S. share increased from 1% in 2008 to 4.5% in 2010 and reached a record value at 4.8% in 2012.

The trade theory does not allow for price discrimination in terms of domestic and international prices under free trade. However, the classical trade theory can be interpreted with the following approach: The lower the international price p^{int} is than the autarky price $p^{I,a}$ in *I*, the larger is the imported quantity $q^{I,D,1} - q^{I,S,1}$, shown in Figure 21. The same logic applies also onto the relationship between the domestic price and the import price. Similarly, the larger the price difference between the domestic price in *E* and the price the importing country is willing to pay for the imported good is, the more the exporting country supplies on the international market, given in Figure 23. This supports the empirically observed drastic growth in the coal imports of China from the U.S. during the period 2009-2012. The diverse price movements of Chinese spot coal price and the coal export price of the U.S. to China (Figure 14) in 2010 justify the spike in the U.S. share in China's coal import market (Figure 13) from 1.12% to 4.51%. The increase in Chinese spot price and the decline in the U.S. export price that are denoted as $p_d^{I,c}$ and $p_f^{I,c}$ in Equation 8 resulted in the strong surge in the relative price of domestic coal price $p_d^{I,c}/p_f^{I,c}$. This changed and increased the relative demand for the imported coal $q_f^{I,c}/q_d^{I,c}$ from the United States. I observe that the share of the U.S. (Figure 13) varied in accordance with the price difference during the period 2009-2013. The price gap widened most in year 2012, at which U.S. share reached a record value. A significant fall in the U.S share can be observed in year 2014. In general, the Asian especially China's energy consumption decelerated in and following the year 2014. In 2015, the net coal import of China has decreased by 61.3% from 2013 level. China's announcement in 2014 on the import tariff restoration to 5-6% and policy of reduction in the import quantity starting from 2015 clearly exhibits the fall of U.S. share to 0.31% in 2015 from 4.39% in 2013. The exact amount of the import quota has not been formally announced, however the implementation of a quota is documented[20]. This implies that the import quantity has been directly constrained and this has raised the U.S. coal export price to China to an exceptional value of ca. 500$/short ton in 2015 shown in Figure 14. The import quota directly restricts the quantity that the exporting country serves either in absolute or in percentage of its total import quantity, as given in Equation 13. In case the quota is binding, which means the quota quantity $(q_f^{E,I,c})^{quota}$ is smaller than the import quantity from *E* to *I* $(q_f^{E,I,c})^*$ which is determined by the the economic system under the prevailing market prices (Equation 14), then the restricted coal quantity raises the domestic price in the importing economy. Figure 22 visualizes the effect of an import quota on the domestic prices in the importing and exporting economies. Trade theory implies that the reduced coal imports from the U.S. increases the coal demand in China and thus raises the domestic Chinese price. Similarly, the reduced supply from the U.S. on the international market increases the coal supply in the U.S. domestic market and thus decreases the domestic price. As a result, it is expected to observe an increased domestic price in China and a fall in the domestic coal price in the United States. An increase in the Chinese coal spot price is not observable in 2015. The discrepancy from the fact that Chinese domestic price has declined contrarily to the trade theory, it might be explained by the diminished coal demand in China. The reduced coal demand in China arose due to lower electricity consumption from the slowdown in energy growth, the policy on the restriction of coal consumption, the environmental regulations and the growing hydro power generation.[21]

Following the drastic fall in the import share of the U.S. coal in 2015, Chinese spot price got back on the upwards and the U.S. export price to China on the downwards trajectory in 2016. The U.S. share increased again in the following two years, reaching to 1.28% in 2017. China has decreased the U.S. share by 0.3% in 2018 to 0.98%. It might by deduced that

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[20] The Coal Hub. (2019). How China uses multiple tools to keep coal imports in check [Article]. Retrieved from: https://thecoalhub.com/how-china-uses-multiple-tools-to-keep-coal-imports-in-check.html

[21] Sagawa, A. (2015). Outlook for international coal market. Retrieved from: https://thecoalhub.com/wp-content/uploads/attach_105.pdf

China's import quota on the U.S. coal has been exercised around 1.30%. Although the price gap between Chinese spot coal price and the U.S. export price (Figure 14) has widened in 2018, the U.S. share has decreased (Figure 13), which is inconsistent with the model (Equation 8) that implies an importing country should increase imports as the relative price of the imported good becomes lower. This might be explained by the prevailing substitution effect between coal and natural gas that is caused by the low LNG export price from the United States to the world. As given in Equation 9, the higher the relative price of the imported coal $p_f^{I,c}$ becomes against the imported natural gas $p_f^{I,g}$, the higher the relative demand of the imported gas $q_f^{I,g}/q_f^{I,c}$ is induced in the importing economy *I*. China kept the LNG import from the U.S. almost at the same level in 2018 as a result of the slight price increase after the drastic fall in the U.S. gas export price. The quota effect on China's U.S. coal import is clearly observable through its inconsistency to the trade economics as the import share varies not accordingly to the price difference between domestic and import markets. The significant fall in the U.S. LNG export price induces a strong substitution of coal by natural gas and thus further contributes to the extenuation of the carbon leakage. European, Chinese and Indian energy markets give strong signals for security of supply consideration and environmental concerns, which consequentially illustrate an example for the global coal-to-gas substitution.

5. Conclusion and Implications

This paper emphasizes that the carbon leakage induced by the U.S. Shale Gas Revolution will not reach to an extent that is expected in the trade economics literature. It is well known and discussed that the abundant shale gas production in the U.S. has led to the significant expansion of coal exports from the U.S. to the world, especially to China. As a result, the carbon leakage which is essentially measured by the international coal trade has grown tremendously.

In this paper, I discuss that the carbon leakage is constrained by two factors. The first factor that constrains the carbon leakage from the U.S. and which, to my best knowledge, has not been taken into account by the leakage literature, is the implementation of the trade restriction measures due to security of supply consideration by the importing economies. As the trade quantity reaches a certain percentage, it creates an energy dependency concern for the importer. Nations exercise import quotas in order to directly constrain the trade quantity to the level that is set by the government. I show that China has exercised an import quota in 2015 and since then and limited the U.S. share in the coal import market to below 1.30%. By restraining the coal import from the U.S., China as one of the world's largest coal consumer has curbed the carbon leakage from the United States to itself. This leads to the statement that carbon leakage may not reach to the extent that is induced within the economic system with one polluting source due to the security of supply consideration. Secondly, the continually increasing shale gas production in the U.S., the carbon leakage has been further constrained by the substitution of coal by natural gas due to the scale effect in the gas production. Both of these factors, the implementation of import quotas due to the security of supply reason and the substitution effect between coal and gas, contribute to the shrinkage of the coal trade and coal market, which leads to deceleration of the carbon leakage. As argued, the data on China's and United States' energy markets showed that the import quota has restricted the coal export volume and coupled with the diminishing coal demand in China and the U.S., it has led to a consistent decrease in U.S. coal production. The vastly expanding U.S. shale gas production has reached beyond satisfying the domestic energy needs and U.S. shale gas has leaked into the international market. The ever cheaper becoming natural gas has accelerated the coal to gas switching given the growing global demand for gas not only because its lesser CO2 content but also because it gets economically more favourable. Indeed, the empirical data supports the increasing LNG trade of the U.S. simultaneous with the shrinking U.S. coal export market. It might be concluded that the economic system induces the replacement of coal market by natural gas market due to the scale production of shale gas, thus it contributes further to the limitation of carbon leakage from the United States.

The global LNG trade has increased by ca. 10% in 2017-2018 on yearly basis and by 12.5% in 2019[22] indicating that the international LNG market is growing. As the U.S. has started to export LNG to China and Europe since 2016, Russia has also intensified the competition with the U.S. shale gas in European market. According to Eurostat data, during 2016-2017 the U.S. has supplied more LNG to Europe than Russia. In 2018 and after, Russia followed a fierce pricing competition in European market and exceeded the United States in terms of the export volume to Europe. These instances have put pricing pressure on the incumbent LNG suppliers of Europe such as Qatar and Nigeria, which leads to an increase in competitiveness and higher liquidity in European LNG market. As the U.S. holds a pricing disadvantage on European LNG market against Russia due to its geographical distance, it may seek to cut prices off and dump its LNG on the Asian market. Besides the fact that natural gas markets are getting more competitive and thus natural gas becomes a fuel with a price advantage compared to the coal, the Chinese government inclines to utilize gas as a cleaner energy not only because of the environmental concern but also as it is economically more favourable. Japan leads world as the largest LNG importer and India as the fourth-largest LNG importer in 2019[23], they both signal together that Asian market faces an increasing LNG demand. Thus, the substitution of coal is complemented by the growing competitiveness in the global LNG market regardless of the diminishing coal demand due to the growing awareness on the environmental concern.

European region has taken strong measures against coal consumption in the energy sector. In 2020, Germany has passed the law to phase-out coal by 2038 at latest[24]. Due to declining coal demand in Europe, the coal price has dropped in 2019 by 39% and in 2020 by 28% on yearly basis. Europe's unwillingness to purchase Russian coal led Russia to gravitate towards Asian market. The consistent fall in coal price since 2019 and China's protectionist approach on trade with the United States led together to China to increase coal imports from Russia and thus a persistent increase of Russian share in China's coal import market. Alone in 2019,

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[23] Statista Database. Major importing countries of liquidified natural gas in 2019. Retrieved from: https://www.statista.com/statistics/274529/major-lng-importing-countries/#:~:text=LNG%20importing%20countries%202019&text=In%202019%2C%20Japan%20imported%20the,total%20global%20imports%20of%20LNG.

[24] Wettengel, J. (2020). Spelling out the coal exit – Germany's phase-out plan [Article].Clean Energy Wire. Retrieved from: https://www.cleanenergywire.org/factsheets/spelling-out-coal-phase-out-germanys-exit-law-draft#:~:text=The%20German%20parliament%20adopted%20the,2038%20at%20the%20very%20latest.

China has increased share of Russian coal by 1.35%. The continual increase of Russian share resembles the coal leakage occurred from the U.S to China as the result of the Shale Gas Revolution during the period 2008-2014. The European coal demand is expected to diminish and therefore Russia inclines to serve China's coal demand at low prices. Same as with carbon leakage from the U.S. to China, it is expected that China will increase the Russian coal share until a certain degree, which has reached 14% in 2019. As the certain percentage has been reached and it becomes to constitute a security of supply threat due to the high energy dependency on Russia, China might implement a quota and limit the net import volume. This implies that carbon leakage from Russia to China will be constrained due to security of supply reason. It is well-known that Russia already competes with the U.S. on European LNG market and Russia may increase the production and the productivity in the coming years as a result of the fierce competition on the international market. As China would limit the coal trade with Russia, Russia may be inclined to decrease coal production and increase the LNG export. Simultaneously, latest environmental and policy measures taken in China lead to the acceleration of coal-to-gas substitution. Eventually, the increasing competition on LNG markets would decrease the LNG prices while expanding its consumption and replace the global coal market to a significant degree.

The substitution between three energy sources coal, natural gas and oil has been mentioned in Section 3 as these energies are available to the consumers for utilization to produce electricity. Another important implication on the future of the energy markets lies in the effects of expanding usage of electric vehicles (EVs). The global volume of EVs is increasing since 2011 till 2018 with growth rates ranging between 46% and 69%. However, the growth rate has declined to 9% in 2019.[25] Besides China being the largest EV market, Europe has intensified the usage of EVs thanks to the stricter CO2 emission reduction targets, the introduction of WLTP (Worldwide Harmonized Light Vehicle Test Procedure)[26] in 2017, which measures the fuel consumption and CO2 emission of vehicles in order to maintain a globally comparable test cycle for passenger vehicles. Especially, the implementation of incentives for promoting electric vehicles such as tax exemptions (VAT, registration tax) and other local benefits such as free parking have significantly contributed into growth of EVs sales in Europe. Norway achieved to turn 39% of its vehicle fleet into electric cars in 2017 from 0.3% in 2010. Netherlands used a tax system that promoted electric vehicles.[27] As a result, Norway led Europe in terms of the cumulated CO2 emission savings from sales of new vehicles by 16% in 2017, Netherlands by 3.31% and Germany by 1.51%.[28] It has been observed where such tax incentives for EVs has been applied, there has been most significant growth in uptake of EVs. Norway and Netherlands count into those countries in Europe. With further domination of electric cars as demonstrated by its share of 2.6% in the global car sales in 2019[29], it is expected that oil might lose its prevalence in the transport

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[26] Worldwide Harmonized Light Vehicle Test Procedure (initiative website of ACEA). What is WLTP and How does it work. Retrieved from: https://www.wltpfacts.eu/what-is-wltp-how-will-it-work/

[27] European Environment Agency. Incentives that promote the purchase of electric vehicles have clear climate-related and environmental benefits. Retrieved from: https://www.eea.europa.eu/themes/transport/electric-vehicles/taxes-and-incentives-promoting-electric

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[29] International Energy Agency. Global EV Outlook 2020. Retrieved from: https://www.iea.org/reports/global-ev-outlook-2020

sector in the future. As the global share of electric vehicles increase, the electricity power should play a larger role in the transport sector subduing oil’s supremacy. Besides the increasing dominance of electric vehicles in passenger fleet, worldwide countries also seek the electrification of public transportation vehicles and superhighways. It can be concluded that as a result of the higher significance of electricity generation in the transport sector, natural gas may capture a significant share of the oil demand and constitute itself as a strong substitute to oil energy. Thus, the manifestation of natural gas as a strong substitute to oil induced by the electrification of the transport sector further contributes to the detachment of the natural gas markets from the oil markets by lowering the prevalence of the gas price indexation to oil. Alongside with the growing competitiveness and liquidity on the LNG markets, worldwide a strong demand pattern is given towards natural gas away from coal and oil, which hold a higher CO_2 content at combustion than natural gas.

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