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Correlates of decreasing domestic coal production and use in electricity generation

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Author’s declaration

No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

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ABSTRACT OF THESIS submitted by:

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To reach the goals put forward in the Paris Climate Agreement, much of the already discovered coal resources will need to stay in the ground. Despite this need to decarbonise the global economy, coal production and use in electricity generation has been increasing at the global level, but there are a number of countries that managed to reduce domestic coal production and use in electricity generation. The thesis used data from the International Energy Agency on the energy balances of those 100 countries in 1974-2014 that produced electricity in the greatest absolute quantities in 2014 to find out about correlates that are associated with decreasing domestic coal production and coal use in electricity generation. By using Pearson product-moment correlation coefficient the research established that there is a significant negative correlation between domestic coal production and imports of natural gas and coal, however, there is not a significant correlation between domestic coal production and the amount of natural gas domestically produced and the share of brown coal in the overall coal production of the country. With regards to coal fired electricity generation, the research found that a decrease in domestic coal production is a necessary condition for coal use to decrease in electricity production, however, nuclear power and other fossil fuel output in the national electricity generation portfolio do not covary with coal use in the sector. Based on the results, for emissions from coal to peak and decrease, international policy should focus on the coal mining practices of countries.

Keywords: coal, coal mining, energy transitions, substitute for coal

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1 Introduction

Anthropogenic emissions of greenhouse gases and the associated global climate change has become an important item on the international political agenda. Following the Paris Agreement in 2015, where the majority of countries pledged to ensure that global warming does not exceed 2 degrees Celsius compared to pre-industrial levels, it is increasingly important to set the global economy on a more sustainable path. According to the Intergovernmental Panel on Climate Change (IPCC), global emissions should peak in the next 20 years and subsequently decline for the Paris commitment to be implemented (IPCC 2014).

Among all sectors within the global economy, it is the energy sector that has the largest contribution to greenhouse gas emissions – 68% in 2016 (International Energy Agency 2016a) – and thus the decarbonisation of this sector will be of primary significance in the fight against the climate change. Coal has a 29% share in the global primary energy supply, however, the coal sector is responsible for 46% of the global carbon emissions, (International Energy Agency 2016a). Within the global primary energy supply, the electricity and heat sector have the single largest contribution to emissions (International Energy Agency 2016a), within which coal was the most often used feedstock, standing just over 40% in 2014 (World Bank 2017).

Despite the apparent and immediate need to decarbonise the energy sector, rapidly industrialising countries such as China and India are expanding coal production and use. While India is currently importing the majority of its coal, it is planning to become self-sufficient in supply by expanding coal mining (Cornot-Gandolphe 2016). In addition, in 2015 over 80 GW of coal-fired generation capacity was under construction, and another 20 GW has been approved for construction in India (Department of Industry and Science of the Australian Government 2015). While India has already been the world's third largest producer of coal in 2015, there are also newcomers to the market, especially among developing nations that did not use much of the resource before. Kenya for instance reports that significant coal reserves have been discovered in 2010-2015 in the country, and hence the development plan of the country now envisions 2,5 GW of additional coal-fired generation capacity to be added by 2020 (Ministry of Energy and Petroleum 2015). It is not only developing nations though that are relying on coal resources, Germany had half of its electricity supply generated from coal in 2014 while the figure stood at 42% for South Korea in the same year (International Energy Agency 2017a). All these developments contradict the imperative that in order to meet the goals put forward in the Paris Agreement, much of the already discovered coal and oil will need to stay in the ground (Meinshausen *et al.* 2009; McGlade & Ekins 2015).

On the other hand, some countries have recently decreased their coal production and use. What, if anything, can we learn from these countries? While there are a number of studies that explore decline in the coal sector in individual countries, particularly in the UK (e.g. Turnheim and Geels 2012; Turnheim and Geels 2013) there is no multi-country analysis of decline of coal production or use in electricity generation Such an analysis could in principle identify prerequisites and common characteristics for the declining use of coal and thus have important implications for the global climate.

The aim of the thesis is to identify common characteristics and correlations among countries that reduce their production of coal and its use in electricity generation. This aim can be further subdivided into specific objectives.

1. To identify those countries where domestically mined coal has decreased significantly and persistently.
2. To identify those countries where coal fired electricity generation has declined significantly and persistently.
3. To identify the correlations that characterise changes in domestic coal production, and
4. To identify the correlations that characterise changes in coal use in electricity generation.

As a first step, the thesis analyses worldwide data from the International Energy Agency on coal and electricity use from 1975-2014 to identify countries where coal production or use in electricity generation has declined significantly and persistently. Objectives 1 and 2 are discussed in sections 5.1 and 5.2 of the thesis. To answer the second set of research questions, the thesis formulates the hypotheses deductively, arguing, based on the literature review that coal and natural gas imports, natural gas production and the prevalence of underground mining show a significant association with changes in domestic coal output, while on the other hand, changes in domestic coal production, availability of nuclear power and the availability of other fossil fuels in the generation portfolio exhibit covariance with coal use in electricity generation. The thesis tests the formulated hypotheses by using a medium-n analysis in which correlations are tested by using the Pearson product-moment correlation coefficient (r) in the changes of the primary energy supply and electricity generation mixes of countries.

The thesis is structured as follows. The introduction is followed by a literature review, bringing together the findings of scholars who have previously identified reasons for declines in national coal industries. Following the literature review, the thesis discusses the research design and methods where the used dataset, applied thresholds are introduced and the methodology for the medium-n analysis is detailed. Then the thesis provides a global and regional overview of coal production and use in electricity generation for the period that is in the focus of the thesis with the intention to set the scene and provide a background for understanding the circumstances in which the set-up hypotheses may exert their effects. The results section introduces the main findings of the thesis, listing the countries that made significant and persistent decreases in their coal industries, which is then followed by the hypotheses testing for correlations in coal production and use in electricity generation. In the discussion part that follows the results section, the findings of the thesis are compared with previously published materials on the topic, to be followed by the conclusion section where the thesis provides policy recommendations for countries that are yet to decarbonise their economies and that are wishing to phase out either coal production or use in electricity generation.

2 Literature review

2.1 Structure of the literature review

The literature review is divided into two major sections. In the first section, the literature review begins with an introduction to energy transitions, thereby providing the context and basis for historical comparisons for an energy transition that targets specifically coal. Then the review briefly describes the reasons – mainly through the experience of the United Kingdom – why countries opted for coal in the past, thereby potentially discovering also factors that are crucial for them to use and produce less of the commodity. This is followed by the detailed description of the United Kingdom, Netherlands and France, why these countries phased out domestic coal production and use in electricity generation. It is mainly in this latter section in which the background and prerequisites are formulated that form the basis of the hypothesis formulation that in turn form the second part of the literature review. In this second part, the review introduces hypotheses for the decline in domestic coal production as well as the decline of coal use in electricity generation. These hypotheses are based on the reviewed literature discussed in part one, complemented by additional, not necessarily country-specific arguments where necessary and feasible.

2.2 Historical energy transitions

Throughout history, there have been a few energy transitions. First, there was the transition from biomass to coal (Figure 1) that happened during the 19th century in most nowadays industrialised countries, however, some developing countries have not yet undergone this transition even today. Secondly, there was the transition from coal to oil in the transport and some countries also shifted from coal to natural gas in electricity and heat production as well. This transition happened in the first half of the century in the developed part of the world (Figure 1), but yet again, this transition is awaiting in some developing countries. An essential characteristic of this transition is that despite the relative importance of coal is declining, in absolute terms the global extraction and use of coal resources is increasing year on year. Many scholars and policy makers point out the need to transition towards non-fossil energy sources in the future in order to reduce greenhouse gas emissions.

Yet there seem to exist a paradox in past and future energy transitions: so far, every energy transition brought about a significant increase in energy demand (Grübler *et al.* 1999). Should the switch to non-carbon intensive energy sources also result in such an effect, it is pivotal that whatever additional primary energy demand will be created, it shall not be satisfied by fossil fuels that are likely to be available even at times when their usage is not justified by climate policy objectives. The challenge should be fought on two fronts though as not only additional energy demand should be met by non-carbon intensive sources, but efforts should also be concentrated on decarbonising the current energy supplies, without any increases in particular. It is for this reason as well why it is so pivotal to understand what the conditions are that resulted in countries to phase out coal in electricity generation or the mining of the commodity itself.

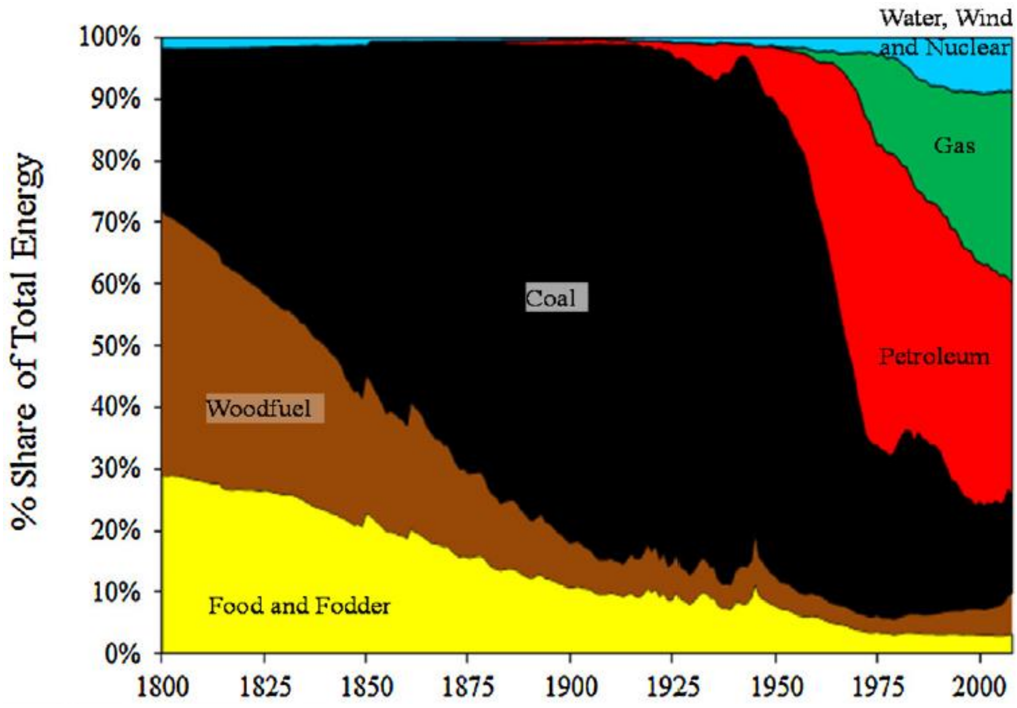

Figure 1: Share of primary energy consumption in Europe 1800-2008 (Fouquet 2016)

The literature on energy transitions has grown rapidly in the past ten years (Fouquet 2016). As such there are a number of definitions that circulate in the literature on what constitutes an energy transition. Hirsch and Jones (2014) provide a rather simple definition by stating that energy transitions are nothing else, but a change in fuels and their associated technologies. Miller *et al.* (2015) on the other hand complement this definition by specifying that the focus on technologies should be on the technologies that exploit the energy resource in question. Fouquet and Pearson (2012) go back to a rather simple definition, however, their focus is on fuels in an economy rather than society, thereby highlighting the importance of monetary issues and prices in energy transitions.

Regardless of the exact definition, the different aspects that each definition works with provides us with some insights into what a decrease in coal mining and use in electricity generation would constitute. Most importantly, based on the above definition and the findings of Grübler *et al.* (1999), a decline in coal usage should be complemented by an at least equal increase in the consumption of some other energy carrier, thereby forming a true transition. But these transitions can happen at various scales. Energy transitions at the macro level are usually concerned with the changes in the patterns of primary energy consumption, however, transitions could happen at smaller scales as well and thus the consideration of coal mining and coal use in electricity generation from the perspective of energy transitions is justified. Therefore, the thesis argues that the definition of energy transitions should be complemented by some level of scope, both geographically and sectorally, for which the thesis will consider a country as an appropriate unit of observation, and country-level coal production and use in electricity generation as the level of observation.

2.2.1 Energy transition from biomass to coal

The factors which influenced previous energy transitions are extensively discussed in the literature. The chain of events that characterise the first energy transition from firewood to coal can be traced back to 18th century England, (Sovacool 2016). Although London received its first coal deliveries in the 13th century, for centuries to come even afterwards, coal was mainly burned by households and the practice was considered to be an act of poverty rather than prosperity (Smil 2010). But this has changed following the 16th century, when coal mining started up at large scales. Humphrey and Stanislaw (1979) identify two main reasons why the surge in coal production happened in Britain and later its associated usage also started to climb. First of all, they note that after the monasteries have been dissolved by Henry VIII, the ownership of mineral rights transferred to private interests who had both the entrepreneurial skills and capital to develop mines. Secondly, they argue that the shortage of woody biomass resulted in the rise in household firewood prices, which ultimately led consumers to substitute away from wood to cheaper energy resources. While some authors do not support the claim that there was a national firewood crisis in Britain at the time (Steinmueller 2013), however, there seems to be growing evidence that at the regional level there were indeed major escalations in prices which high transportation costs could not equal out (Smil 2010).

It is worth to point out that factors that have led one country to switch to the increased use of coal resources may not have been prevalent in other countries that also exhibited a similar transition to the first fossil fuels. Smil (2010) points out for instance that although Germany, being a periphery rather than a core country in the transition (Sovacool 2016), made the switch over to coal resources even though biomass, fuelwood and charcoal were still easily available and large parts of the country were forested even at the end of the 19th century. This highlights the heterogeneity of the chain of events which ultimately lead to the same outcome, the increased share of coal resources in the overall primary energy supply.

While the structure of mineral resource ownership and prices of substituting products could be identified as major influencing factors in the core country (UK), technological advancements and changes in the use of the resource further ensured the boom in the use of the product. While at the beginning of the 17th century when coal production was already elevated in the country, the vast majority of the commodity was used for household applications (heating and cooking) and not for industrial purposes (Flinn 1984), which in itself could not have happened without technological innovations as the structure and heating equipment of households had to be basically redesigned in their entirety (Allen 2012). By the end of the century the usage patterns started to change significantly, skewing towards industrial rather than household application of the commodity, a process which again was aided by technological development. Even though the steam engine and its constituting parts were developed in mainland Europe, yet it was Britain where the technology first achieved commercial success. Allen (2012) argues that nowhere else could have steam engines gain any relevance at the time other than Britain, where the need to dewater mines created positive incentives to use the technology, ultimately creating a positive feedback effect where better dewatered mines provided better conditions to extract coal at a large scale. Although it was the mining industry in which the industrial usage of coal first gained significance, however, this was only a stepping stone. By deploying steam engines at ever greater sizes and numbers, the efficiency, reliability and size of the technology improved to the extent that soon they also revolutionised railway transport, which again created positive feedback effects for the mining sector, as now the commodity was easier to transport to longer distances.

Overall therefore three main factors could be highlighted from Britain's experience from switching from biomass to coal. First of all, the changes in mineral ownership concentrated rights into private interests, which had the entrepreneurial skills and required capital to start up coal production at large scales when demand increased for coal, being a substitute commodity to firewood that became increasingly scarce and expensive (Jefferson 2015). While these created the basis for the expansion of coal use and mining, technological advancements, such as those that relate to the efficient and safe burning of coal in households and the invention and incremental refining of the steam engine, created a further augmenting effect for coal demand and supply, which ultimately shifted from being a predominantly household fuel to the fuel that drove industrialisation at large scales.

Following the UK, coal started its world-wide conquest and became the number one source of primary energy in the early 20th century at the global level, this is when for the first time in history more energy was derived from coal than from biomass. During the 20th century though, the global coal industry underwent some major changes, ultimately losing its significance as the number one source of primary energy by 1970, when oil has taken over (Figure 2). This is marked as the second energy transition in the world, when oil took off and some extent replaced coal in the primary energy mix, especially in the transport sector. As already discussed earlier, this energy transition just as previous ones were marked by a major increase in energy demand, therefore rather interestingly while the share of coal decreased, its absolute production and usage did not.

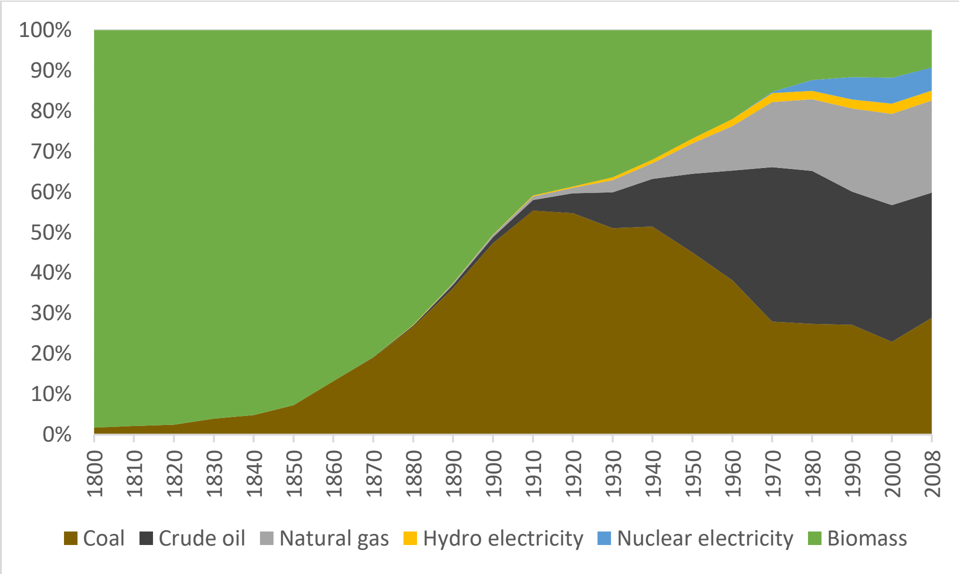

Figure 2: Global primary energy consumption 1800-2008 (Based on Smil 2010)

While at the global level the absolute size of the industry did not decrease in the second part of the 20th century, but it is in this period when for the first time in modern energy history, some countries started to face away from both coal production and usage in the electricity sector, which became the most important usage alternative of the commodity by the second part of the 20th century. The experiences of these countries in this period are therefore of primary significance considering the purposes of the thesis.

2.2.2 The United Kingdom

While the United Kingdom was the pioneer in first using coal at large scales it is also one of the most prominent cases of coal losing its significance and being gradually phased out.

Common knowledge often accuses Thatcherism as being the major cause for the decline of the UK coal industry, however, Turnheim and Geels (2012) show that the industry has been on a declining trend almost from the turn of the 20th century (Figure 3). After centuries of continuous expansion, the interwar periods brought about a halt in the production and use of coal. Following the world wars, as a result of reconstruction efforts, the importance of coal increased for a short period of time, resembling the pre-peak times before 1913, however, from the 1960 onwards the industry entered into a major phase of decline. While Turnheim and Geels (2012) note that the energy transitions of coal in the primary energy mix and as an input into electricity generation are ultimately different series of events, the same explanatory variables can explain the downturn of coal at all scales in the UK.

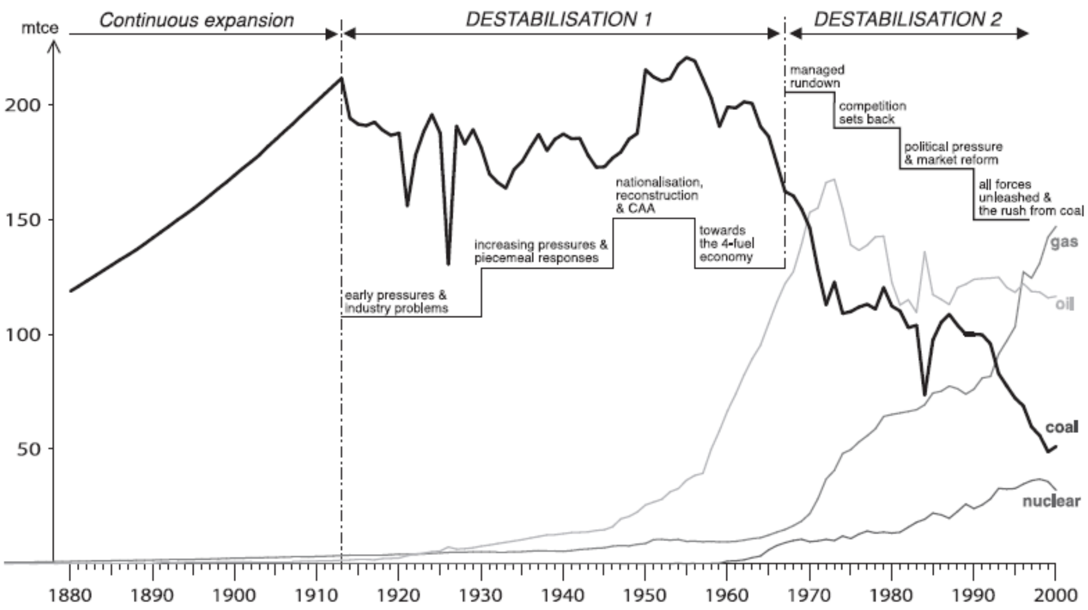

Figure 3: British transition in primary energy sources and an outline of the destabilisation pattern for two historical cases (Turnheim and Geels 2012)

In the early destabilisation of the industry, Turnheim and Geels (2013) argue that Britain has lost a large share of its export markets, as a result of which the demand for coal production decreased. Other authors also note that domestic production issues also threatened the existence of the industry later in the century, Glyn and Machin (1997) argue that coal production became increasingly unprofitable with time threatened by cheaper imports while Parker (1993) also adds that coal favourable resources had become depleted by the second part of the 20th century.

Turnheim and Geels (2013) highlight the following factors as destabilising factors for the British coal industry from 1956. Coal exports at that time were already not significant, the only lifeline of the industry was electricity generation. However, from 1960 onwards the UK was slowly transitioning towards a four-fuel economy, based on coal, gas, oil and nuclear power, the latter three being increasingly prevalent starting from the 1970s. Their views are further supplemented by Parker (1993) who also recognized that the discovery and production of the North Sea oil and gas reserves helped the UK to diversify away from coal, especially following the privatization of the UK electricity market (Parker and Surrey 1993).

Based on Turnheim and Geels (2013), public awareness and perceptions also had a role to play: coal was increasingly viewed as an outdated and less attractive energy resource, especially for households. This shift in perceptions is likely to have been influenced by events such as the Great Smog of London in 1952 when the 4.000 associated deaths created serious public concern (Wilkins 1954). This lead to the enactment of the 1956 Clean Air Act, which introduced the need to use smokeless fuels in households and often is regarded as a milestone of environmental legislation

(Brimblecombe 2007). Such public perceptions also had a role to play in the enactment of the 1965 White Paper on Fuels Policy, which defined fuels policy in the context of national economic policy coupled with an urge for energy independence (Pearson 1981). As at the time there was an import ban on coal in the UK and the industry was already suffering from the destabilisation characteristics discussed before, it is of no wonder that the White Paper envisaged the future of UK energy based on four energy carriers instead of just one. Since economic considerations were given great importance, the White Paper was highly supportive of North Sea oil and gas exploration, which ultimately replaced a large share of coal fired power generation in the country (Figure 4).

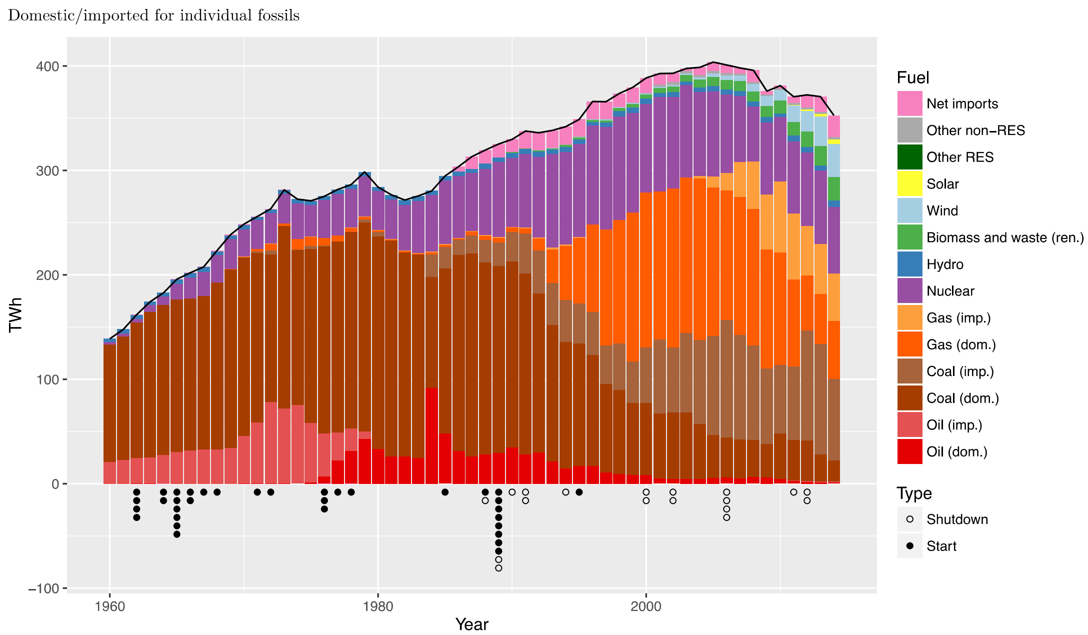

Figure 4: Electricity mix in the UK (International Energy Agency 2017b)

A further explanation to the demise of the domestic coal production is the inability of the sector to switch to the more profitable open pit mining. Globally and historically speaking, the share of open pit mining has been gradually increasing, as a result of more favourable mining economics, as with open cast mining more of the resource can be extracted (Chadwick *et al.* 1987). In the UK, Figure 5 shows that this trend in the industry, to mine more open-pit rather than underground, although appeared, it did so rather late, when the coal sector was already under significant pressure. Even in 1983-1992, at the height of the UK coal mining industry conflict, close to 80% of the mines were deep shaft mines, which explains the low profitability of the sector and also government policy that aimed to stop supporting the industry at large scales. The shift towards open pit mines continued well into the 21st century, as in 2015 the last two underground coal mines closed in 2015 (Euracoal 2017).

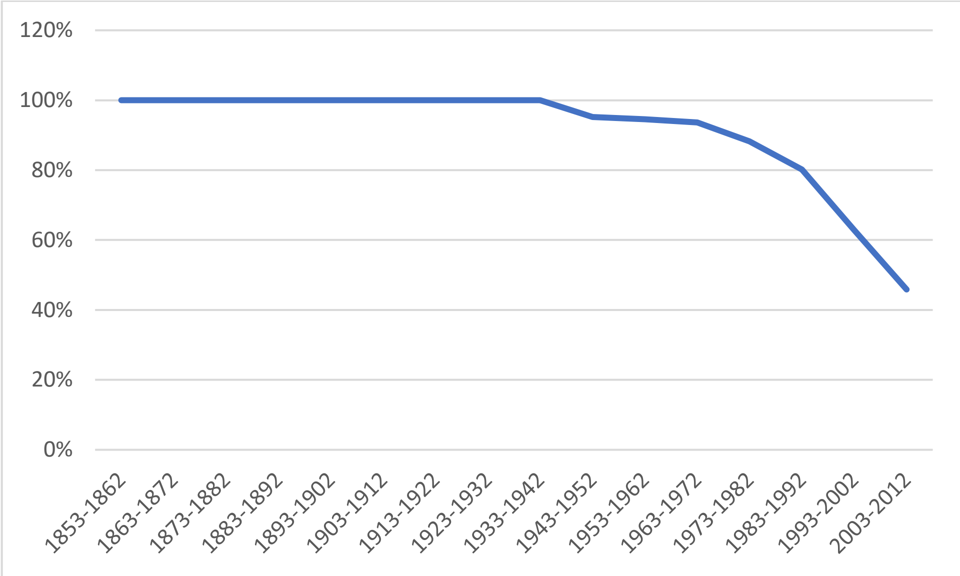

Figure 5: Share of coal mined in underground mines in the United Kingdom 1853-2012 (Department for Business, Energy & Industrial Strategy 2016)

In summary, the UK ultimately transformed itself from being the pioneer of the coal industry into a nation that in 2017 first experienced a day with no coal used at all in its electricity mix (Bloomberg 2017). This change in the use of coal can be explained by a continuously declining resource base and uncompetitive mining practices that became increasingly challenged by cheaper imports. Public perceptions and awareness of the potential negative health consequences of uncontrolled coal burning was also responsible for developing a rather hostile public attitude towards the commodity, which could have further aided the government that adopted measures which favoured not only a single-fuel economy, but by exercising energy policy through economic policies, the exploration and exploitation of North Sea natural gas and coal reserves became a central tenet of government objectives. In addition, the mining sector could not shift significantly towards open pit mining in the country, as the resources of hard coal are three times as abundant as of lignite in the country, and only 80 million tonnes of reserves are located in near surface formations, amounting to just ¼ of economically recoverable reserves in the country (Euracoal 2017).

2.2.3 Netherlands

Smil (2010 and 2017) provides an excellent summary of the decline in coal production in the Netherlands and the decrease of the use of the commodity in electricity generation. Despite the presence of domestic coal resources, industrialisation in the Netherlands was primarily driven by imported coal from neighbouring Britain and Germany and large scale domestic production only started up at the end of the 19th century. Coal production reached its peak in the 1930s in the country, maintaining close to maximum production levels up until the middle of the century, then starting a significant decline during the 1950s when the supergiant Groningen gas field was discovered.

The decline of the coal industry can be explained by the following chain of events. First of all, technological advancements made it possible for households to use gas both for cooking and heating purposes, but in the middle of the 1960s when most households already converted to the usage of gas, there was still plenty of natural gas left for exports. In 1965, the government drafted a 10-year plan to phase out coal production, which was concentrated in the Limburg region of the country, which ultimately resulted in the disappearance of traditional coal mining livelihoods of 45.000 people directly, but with the indirect effects considered as well, more than 200.000 people were affected (Smil 2010). The government measures that ensured this transition included the relocation of some government offices to the affected region and perhaps most importantly the state mining company, *Staatsmijnen*, was given a 40% share in the development of the Groningen gas field, a result of which the company transformed itself into a multinational conglomerate, nowadays producing a large variety of products from natural gas, and has also become active in other sectors such as health and nutrition. As a result of these measures, the country ceased coal production according to the plans initiated in 1965 by 1975.

Coal use in electricity generation in the Netherlands however, has not declined so steeply over time (Figure 6). Following the development of the hydrocarbons sector in the country, oil and natural gas overtook coal as the primary input into power generation and by the beginning of the 1970s coal maintained only a small amount of its share in power generation. Most importantly though, coal was first threatened by imported oil products in electricity generation, and only after the importance of coal has somewhat shrunk, came the discovery and wide-scale development of domestic natural gas and oil based generation. This shift towards oil and especially natural gas was further aided by perceptions at the time that natural gas should be produced and used as quickly as possible, as the popular belief was that nuclear energy was perceived to become the sole source of electricity, and thereby natural gas reserves should be developed and tapped before the large-scale advancement of nuclear power (Smil 2010).

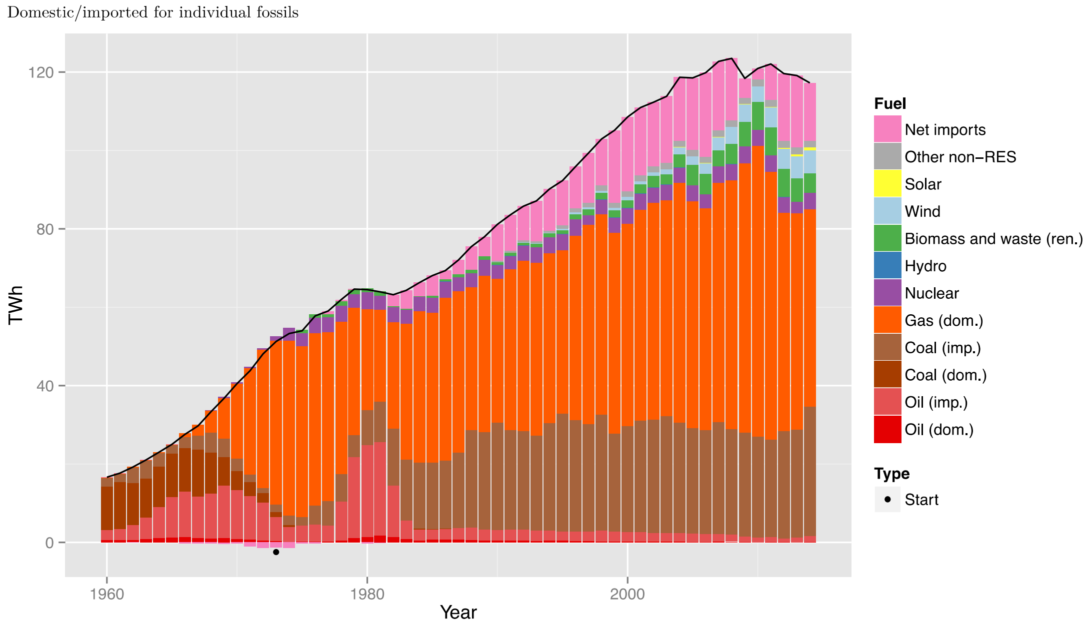

Figure 6: Netherlands electricity generation mix (International Energy Agency 2017b)

From a historical perspective, it is now clear that nuclear power failed to substantially increase its share in power generation, in fact following the oil crises in the 1970s coal had a renaissance in the Dutch energy mix. Verbong and Geels (2007) writes that the second global oil crises exposed the country too much to skyrocketing oil and linked gas prices, therefore policy started to favour coal again, which had to be imported to the country. This process did not change substantially in recent years, the Netherlands is experiencing increased coal usage in power generation even nowadays.

Overall, the discovery and development of other fossil fuel reserves domestically played a major role in the demise of the Dutch coal production industry and similar reasons also led to the phase-out of the commodity in electricity generation, only to be reintroduced after the global oil crises. Some 50 years before present though, natural gas pricing was almost exclusively linked to oil prices, therefore the oil price shocks creeped into the natural gas market as well, thereby largely affecting the natural gas producer Netherlands, which ultimately led to the revived interest in coal fired electricity generation, for which the commodity was imported after the 1970s rather than produced domestically.

2.2.4 France

The share of coal in primary energy consumption reached 50% in France by 1870s (Smil 2016), and its maximum just before the 1950s when oil became the most important source of primary energy (Smil 2010). France, however, was not as blessed as the United Kingdom or the Netherlands in terms of fossil fuel endowment. Already during the middle of the 19th century, the country was facing a slowly but steadily decreasing coal resource base, and the availability of alternative domestic fossil fuels was also limited. Furthermore, the coal reserves were dispersed in the country, which made the transportation of the commodity more expensive, as economies of scale could not operate at such high levels (Didier 2008). These factors meant that domestic coal was easily contested by other alternative sources of energy, and coal soon lost its significance in the primary energy mix, as large-scale usage of oil soon became wide-spread both in transport and electricity generation (Figure 7).

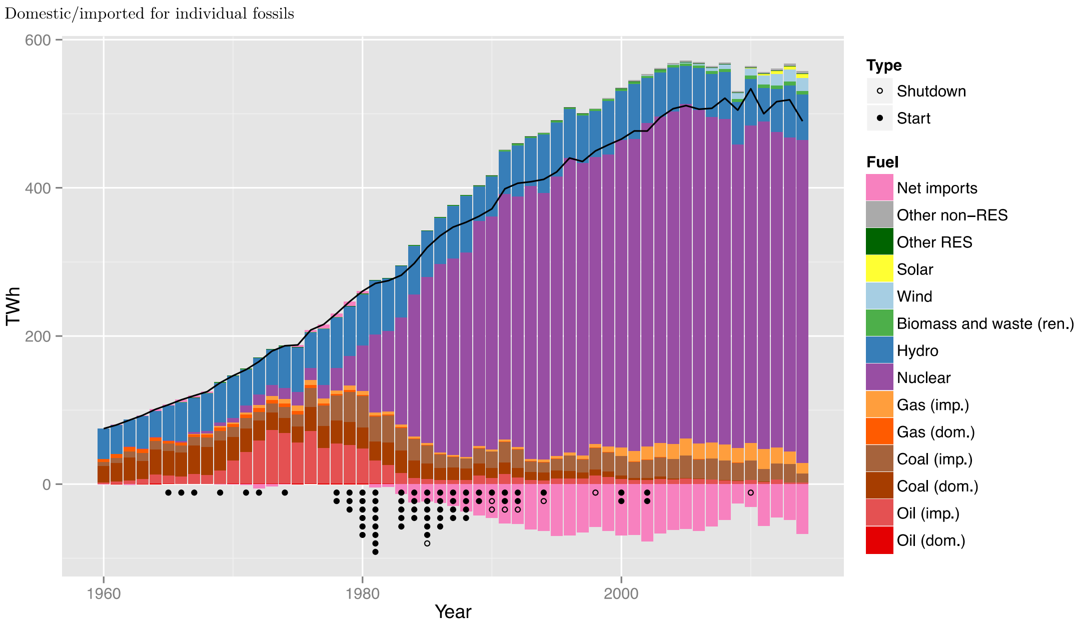

Figure 7: Electricity mix in France (International Energy Agency 2017b)

Akin to the Netherlands though, France had to rethink their energy policy following the first oil crisis of 1973, ultimately deciding on the large-scale deployment of nuclear power because of aspirations for security of supply and independence from imports (Gralla *et al.* 2017). The country could not turn back to using more domestically produced coal because of the exhaustion of the domestic mines (Didier 2008), and energy independence became such an important theme that large scale imported coal was not considered as a real option. Faced by this dilemma, the country embarked on the domestic development of major nuclear capacities encapsulated in the Messmer Plan of 1974. The Plan initiated the wide-scale roll-out of a specific type of pressurized water reactor, based on American technology and built only in two sizes (Smil 2017). The standardisation of the industry helped the roll-out to happen at a fast pace, while the strategic location and even distribution of power plants were supposed to ease the load issues created by such a large non-flexible capacity addition.

The French experience further sheds light on why countries may decide to phase out coal production and use in electricity generation. The slowly exhausting mines and their dispersed spatial distribution made the industry less competitive compared to other fossil fuels, thereby providing the opportunity for oil to compete on a cost basis. France's reaction to the 1970s oil crises is rather unique, it is the only large economy of the world that has such a large share of nuclear power in electricity generation. While nuclear power did not directly supersede coal in the greatest terms, the increase in the usage of oil in the primary energy max was greater, however, the expansion of the nuclear power station fleet occurred in line with a continuous decline in coal fired electricity generation, therefore the availability and expansion of nuclear capacities could be negatively correlated with coal fired electricity generation.

2.3 Grades of coal

The grade and associated qualities of coal determine its best usage alternatives. Understanding the differences between the four different main coal grades, is crucial to understanding the reasons why one kind of coal may be phased out yet keeping another is still being produced and used.

Miller (2005) gives an excellent introduction into the different grades of coal. Commercially speaking, there are two major coal-classification schemes, one mostly used in North America and developed by the American Society for Testing Materials, while the other one most often used in Europe and developed by the United Nations Economic Commission for Europe. Both classification systems are based on the content of volatile organic matter, moisture and fixed carbon based on which the four larger categories of coal emerge:

- Anthracite (black coal)
- Bituminous (black coal),
- Subbituminous (brown coal),
- Lignite (brown coal).

The above list is arranged by decreasing quality, lower grades of coal correspond to its lower heating value. Low grade coals are high in moisture and rich in volatile organic matter, in fact remnants of coalified plants can still be discovered in lignite, and lignite is also susceptible to spontaneous ignition (Singh 2004). Geologically speaking the lower grades of coal, such as lignite and subbituminous, are of more recent origin, being generally less than 50 million years old while higher grade coals such as anthracite and bituminous coal could have an age up to 300-350 million years (Miller 2005). This means that lower grades of coal are likely to be mined cheaper as well. Lignite and subbituminous coals spent less time underground during their formation, therefore their deposits are usually closer to the surface and are thicker, while higher grades of coal are generally found in deeper deposits, and the deposits themselves are thinner (Singh 2004). Consequently, the mining of lignite and subbituminous coal (collectively brown coal) can be easily accomplished from the surface, using open-pit mines and large earth-moving machinery, while higher grades of coal tend to be mined in underground mines, and be more labour intensive.

From an economic point of view, lower grades of coal are more expensive to transport and store (in relation to their heating value). Higher grades of coal, on the other hand, have a lower concentration of organic compounds, higher rates of fixed carbon content, and lack of moisture locked within the formations, all of which increase their heating value and make them easier to burn and handle. Ash and sulphur content of coal is decreasing with grade, therefore the potential environmental impact of lower grade coals is larger.

2.4 Uses of coal

Coal has been an essential resource for centuries, with various uses and sectors accounting for the increasing demand. In modern times, the important differentiation should be made between coking coal and steaming coal. Coke is a fuel used in metallurgy that is derived from the baking of high quality coal in an anaerobic environment, thereby removing impurities found in coal. Coking coal is primarily used in steel and iron production, and it is generally the higher quality (anthracite and bituminous) grades that are best suitable for making coke. Steaming coal is used in thermal power plants to produce electricity and is generally of lower quality (lignite, sub-bituminous and bituminous.

Historically speaking, the share of coal that is used for electricity generation is increasing over time. While in 1971 only about 45% of all extracted coal was used for electricity generation, this has increased to 70% at the turn on the millennium and has levelled out just below that in the past 15 years (Figure 8). In absolute terms, the amount of coking coal used has not decreased globally with the increasing use of the commodity in electricity generation, as the amount of steel and iron produced has been increasing continuously (International Energy Agency 2016b).

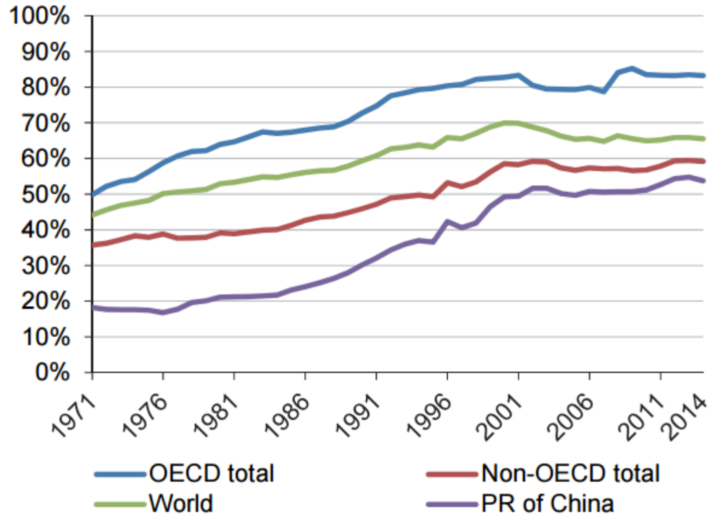

Figure 8: Percentage of primary coal used for electricity and commercial heat production 1971-2014 (International Energy Agency 2016b)

While electricity and heat generation and coking applications of coal dominate the usage of the sector, there are other significant coal uses in individual countries. Household consumption of coal used to be for instance rather significant, and in some countries, such as India it is still growing (International Energy Agency 2017b). Historically speaking, coal used to be an important fuel for transportation, however, in modern times this became less pronounced. Coal, however, is still an important fuel or feedstock in other energy intensive industries such as cement production or smelting, where often coal is burned to produce the heat that is needed for the cement kilns to run (World Coal Institute 2005). In addition, coal has many properties useful for chemical industries. Before the advance of natural gas and electricity, coal was used to produce coal gas or more colloquially known as 'town gas' for lighting and heating purposes. Coal was also used historically to manufacture liquid fuels to be used in transportation, however, this was a measure that only countries that experienced significant economic hardship opted for, including Germany during the II. World War and South Africa during the embargo. South Africa has kept its coal-to-liquids production capacities and is still manufacturing liquid transportation fuels this way (World Coal Institute 2005). Chemical industries are still using coal both as a feedstock and an input material, producing for instance naphthalene, phenol or active carbon to be used in water and air filters, or carbon fibre to be used as a light-weight construction material.

Given these diverse uses of coal, it is essential to remember that while it can be phased out in electricity and heat production and reduced in coking, some coal usage such as in the manufacturing of certain dyes, active carbon or carbon fibre is unavoidable. From a global environmental perspective though industrial applications of coal contribute much less GHG emissions than burning of coal in power stations (International Energy Agency 2016c) which is the focus of this thesis.

2.5 Reserves of coal

The terms reserves and resources are often used interchangeably; however, they refer to two distinctively different groups of mineral resources, and the distinction is important to draw when reflecting upon a country's commercially exploitable coal deposits. The thesis here discusses the American categorisation of reserves. Reserves refer to those deposits of coal that are measured and indicated and are economic to extract. Resources are currently sub-economic to produce, even if there is adequate geological knowledge about these formations. The third category that is important to distinguish is the undiscovered resources, about which geological knowledge is incomplete, there is only indirect evidence for the existence of these resources (Figure 9).

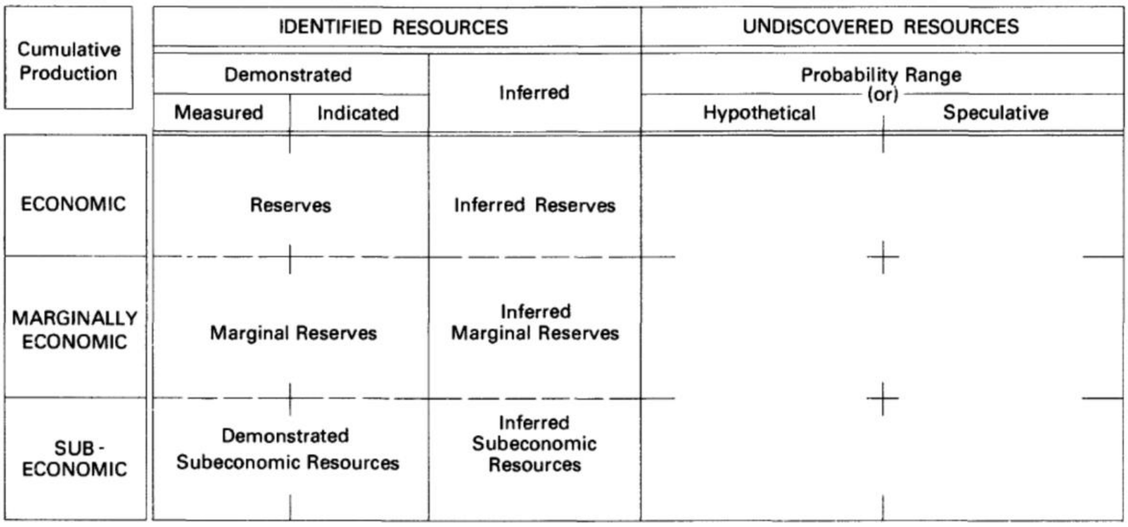

Figure 9: Coal resource classification developed by the United States Geological Survay (European Commission 2012)

The important feature of mineral categorisation is that the categories, reserves and resources are dynamic concepts and based on the price of the commodity or the available technology, reserves can be reclassified into resources and vice versa as well as indicated by the bidirectional arrows in Figure 10.

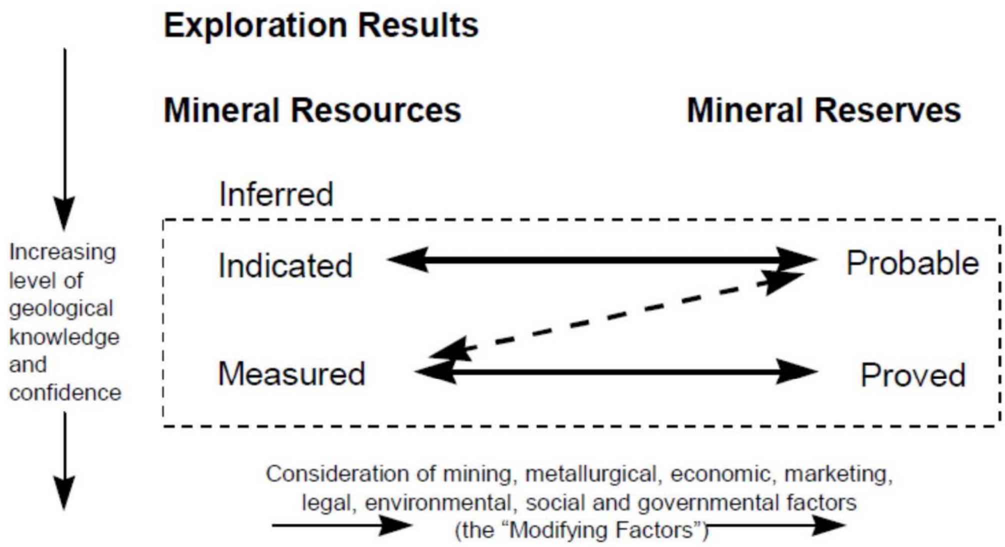

Figure 10: General relationship between exploration results, mineral resources and mineral reserves (European Commission 2012)

Global coal reserves are somewhat difficult to estimate, as there are major differences in the way certain regions account for the quality of their reserves, a difference that is even more challenging from a historical perspective. For instance, the definitions of Australian and American coal categories as defined by the Joint Ore Reserve Committee (JORC) code in Australia (The Minerals Institute 2012) and the United States Geological Survey (United States Geological Survey n.d.) are diverging. Therefore, this thesis presents two sets of global reserve estimates, between 1987 and 2015.

Shafiee and Topal (2009) provide a historical view on global coal reserves from 1987 to 2005 (Figure 11). In this time period, global coal reserves diminished quickly from 1,5 trillion tonnes to just above 1 trillion in 1990. This was followed by a ten-year period when global coal reserves remained stable close to 1 trillion tonnes, to set onto a declining path from the turn on the millennium again, after which reserve levels reached 800 billion tonnes. At the 2005 rate of consumption, this amount of coal would have been sufficient enough to meet a stagnating demand for more than 200 years.

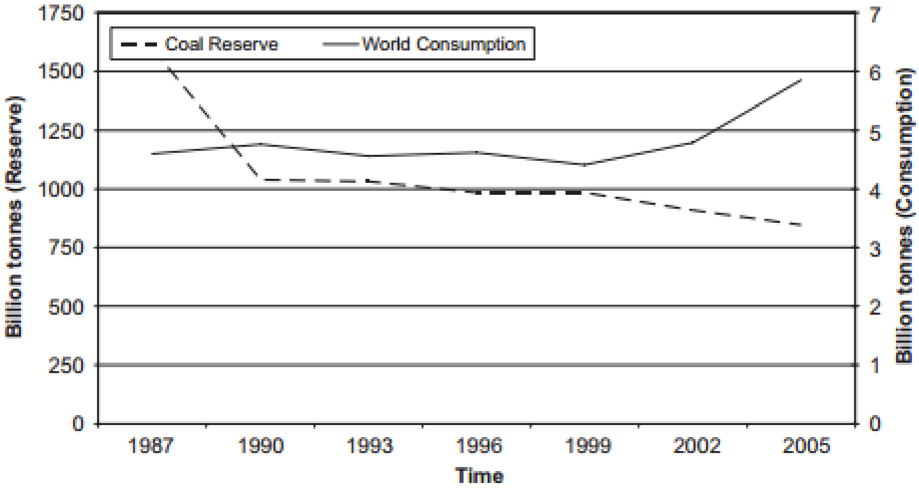

Figure 11: Global coal reserves and consumption 1987-2005 (Shafiee and Topal 2009)

To construct the global reserves from 2005 to present, the thesis turns to a different data source, BP's yearly publications about world energy trends. Their recent publication suggests that in 2015, global coal reserves amounted to 891 billion tonnes, therefore slightly above the levels as published by Shafiee and Topal in 2005, however, the reserves to production ratio, has declined to just above 100 years (BP 2016) from 200 years in 2005. Interestingly, while the reserves of other fossil fuels, such as oil and gas have continued to increase along the years, the reserves of coal are continuously diminishing. Nevertheless, coal reserves are still vast in comparison, both oil and gas have reserves to production ratios just above 50 years (BP 2016).

2.6 Carbon emissions from coal

Despite the need to decrease carbon emissions globally, the global share of coal emissions in all carbon-dioxide emissions is growing. While in 1975 emissions from coal only accounted for 36% of the total emissions, this has increased to 46% in recent years. Although in the past years the share did not increase significantly, in fact a mild stabilisation has also occurred (Figure 12), but the fact that nearly every second carbon-dioxide molecule that is released into the atmosphere is of coal origin truly speaks for the wide-scale use of the commodity that should be decreased as soon as possible.

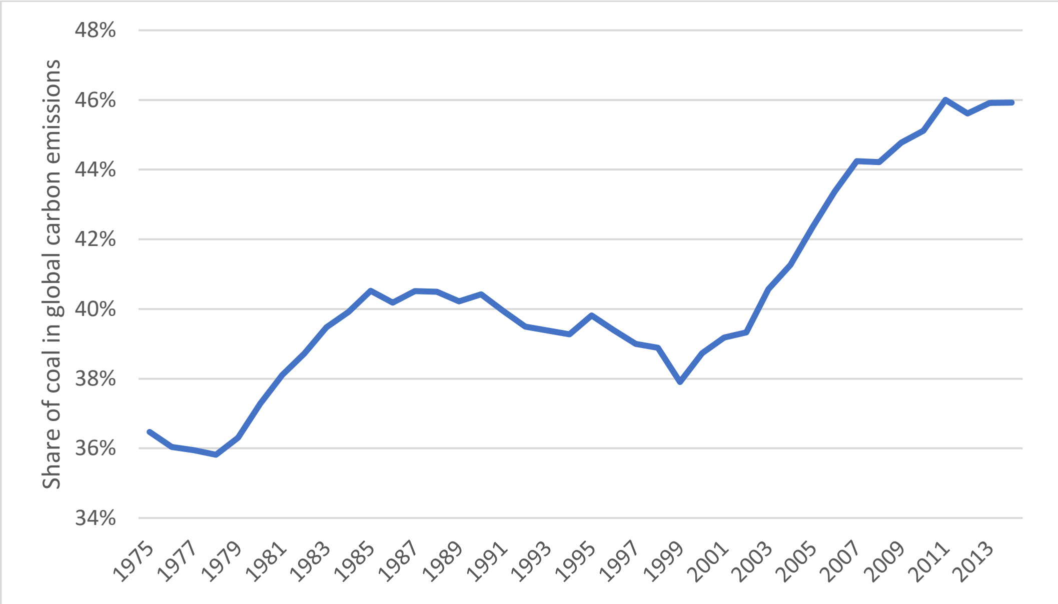

Figure 12: share of coal in global carbon emissions (International Energy Agency 2016c)

Not only does coal account for almost half of the global carbon-dioxide emissions in relative terms, but its contribution among all fossil fuels is also the greatest. While in 1975 carbon-dioxide emissions from oil were almost 2 billion tonnes more than from coal, oil's lead has been slowly decreasing and from the turn of the millennium coal emissions have greatly surpassed those of oil and gas (Figure 13).

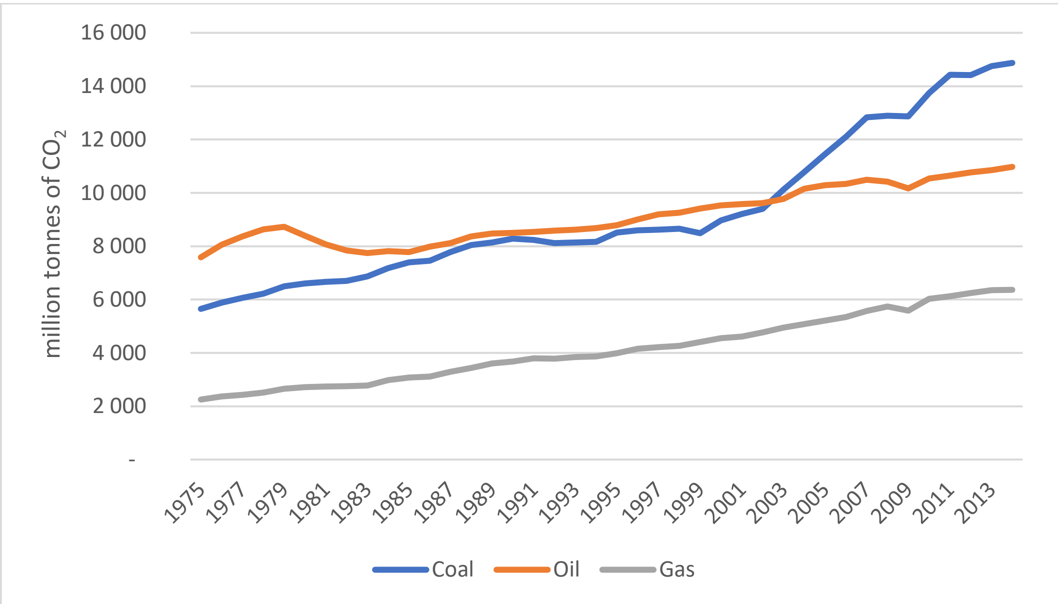

Figure 13: Carbon-dioxide emissions from fossil fuels (International Energy Agency 2016c)

2.7 Causes of decline in domestic coal mining

In this section, the thesis organises the common themes and experiences across countries to decrease domestic coal production and use in electricity generation into hypotheses that could potentially explain such patterns in other countries as well.

2.7.1 Availability of other fossil fuel resources

Based on the reviewed evidence, both the UK and the Netherlands substantially increased hydrocarbon productions at times when the coal industry was already deteriorating, perhaps more notably in the Netherlands than in the United Kingdom. This was made possible by the then recent discoveries of hydrocarbon reserves of rather large sizes, as the Groningen gas field is considered as a supergiant field by itself, while the discoveries in the North Sea also revealed some larger deposits, such as the giant Brent oil field. While from a contemporary point of view the subjects of these discoveries do not represent modern energy carriers, in the 1960s and 1970s oil and gas were truly perceived as modern fuels compared to coal, therefore their development was rather perceived as desirable.

2.7.2 Availability of coal and natural gas imports

A potential explanatory variable for the decrease in coal production is the availability of coal and natural gas imports to replace domestically produced coal. While from an environmental perspective this may not represent a superior outcome, only a displacement and export of pollution from mining, however, as the case of the Netherlands showed it, after domestic coal production was phased out, it was import coal resources that made up for the increase in coal demand. In the absence of such measures, it could be argued that coal production would have declined more pronouncedly. Yet added to the case of the Netherlands, the thesis considers it important to add the imports of natural gas as well, as the two feedstocks can often be substitutes of each other in their applications.

2.7.3 Prevalence of underground mining

Although not discussed at the country level before, the prevalence of underground mining could be a crucial factor in a declining coal mining industry. As already discussed in the previous chapter, the advance of open cut mining in the global coal industry brought about significant cost decreases, as significantly more coal can be extracted from the seams if mined open cut than underground (Singh 2004). While in the UK, open cut mining was non-existent up until the 1920s when already the industry was producing lower levels of output, but even at the turn of the century, the industry was still mining deep shaft mines instead of open pit ones. The economics of underground mines are not as favourable as open shaft mines, therefore it is not surprising that imported coal and other energy resources were able to compete with domestically mined coal. Germany on the contrary, had managed to open up large open cast mines from the 1960 and in fact German policy is planning to phase out hard coal produced mostly in underground mines by 2018, while open pit coal mines shall prevail (Renn and Marshall 2016). Conclusively, it is arguable that domestic coal mining will decline in those cases when the industry has not managed to shift to the more economic technique of open-cut mining, led either by the characteristics of the resource heritage or the structural inability to do so of the industry, as a result of government policy.

2.8 Causes of decreasing coal use in electricity generation

2.8.1 Decline in domestic coal mining

As the previously discussed case studies demonstrate in the case of France and the UK, the demise of the domestic coal mining sector has also brought about a change in the electricity generation portfolio. In the UK, the decline in coal production meant a higher share of natural gas used instead of coal and eventually the absolute share of natural gas also exceeded the level of production from coal. In the case of the Netherlands this transition was even more forceful and guided by policy at the time, even though coal was reintroduced from imported sources following the oil crises. In France, the decline in mining was also associated with lower outputs from coal fired stations, however, the nuclear capacities that entered the market provided rather for additional demand, other than replacing coal-fired generation.

2.8.2 Availability of nuclear power

A daily national electricity load curve has a highly similar profile in almost all countries in the world. In off-peak periods when demand is low, electricity is usually generated by technologies that are at the bottom of the electricity generation merit order, thereby their cost of generation is low, however, the load following capacity of these power stations are limited at their best, hence they are most economically run for extended periods of time, without significant changes in output. Traditionally, hydropower and coal-fired power plants provided the majority of base-load electricity, however, with the advancement of civil nuclear technologies and their use in electricity generation in the second part of the 20th century, these two base-load technologies were increasingly contested or complemented by nuclear power as well in certain countries.

Jasper (1990) provides a great insight into the potential interaction of nuclear and coal-fired electricity generation. He notes that prior to the oil-crises in the 1970s, fossil fuel availability did not have an apparent effect on the development of nuclear power, however, after the oil crises countries became much more aware of the effects the non-availability of imported energy resources may cause. In the US, the vast coal reserves ensured the political leadership about a safe domestic backup source of energy, resulting in more coal-fired generation constructed than nuclear, even though it was the US that constructed the most nuclear reactors in absolute terms. In Europe though, the lack of resources in both France and Sweden pushed these countries to opt for nuclear as a substituting source of base-load power. Despite common motivations, France opted for the significant build-up of nuclear expertise and know-how, as policy makers perceived the issue rather as a supply shortage, while in Sweden nuclear policies were also complemented by electricity conservation efforts (Jasper 1990), similarly to Japan and Germany. Recent empirical evidence also suggests that nuclear power indeed could be a substitute for coal based generation. Just a year ago, when French authorities discovered a potential risk in 18 of their 58 nuclear reactors and had them shut down for inspection (The Economist 2016), it was fossil fuels, mainly coal that filled in the gap in supply. Regardless of the previously discussed motivations, these two examples show that nuclear power could serve as a substitute to coal-fired generation, therefore the presence or emergence of nuclear based power generation may be associated with a decrease in coal use in electricity generation.

2.8.3 Availability of other fuels for electricity generation

The hypothesis in this case is similar to the one described in the decrease in coal mining section. All three countries whose energy transitions have been discussed in detail before experienced declining shares of coal inputs into electricity production, replaced by hydrocarbons that have either been produced domestically as in the case of the UK and the Netherlands, or imported as it happened in the case of oil and France. Therefore, the thesis argues that the availability of other fossil fuels could be negatively correlated with the use of coal in electricity generation.

2.9 Summary of hypotheses

Table 1 provides an overview of the proposed and identified hypotheses based on the literature review that could explain why countries decreased domestic coal production in the past and use in electricity generation.

Table 1: Summary of hypotheses

	Reason
Reasons to decrease domestic coal mining	Availability of other domestic fossil fuel resources
	Availability of imports of coal and natural gas
	Prevalence of underground mining
Reasons to decrease coal use in electricity generation	Decline in domestic coal mining
	Availability of nuclear power
	Availability of other fossil fuels in the generation portfolio

3 Research design

3.1 Description of the datasets

I used the database of historical world energy balances from the International Energy Agency (2017b), which has been processed into two larger datasets. The first dataset contains information about coal production, trade and usage in absolute units (ktoe). Altogether 143 countries were included in this dataset, with data on coal production, imports, exports, amount in total primary energy supply, use in electricity, use in combined heat and electricity generation, use in heat production, total final consumption, industrial use, use in transport, residential and use in services, use in agriculture and forestry, non-specified use and finally non-energy use. This dataset was first of all used to provide a source of information in absolute terms, while it was also used to provide some basic background to the research. This dataset runs from 1960-2015, however, 2015 values are only available for coal production, imports and exports.

The second dataset is based on the previously described dataset; however, it only contains 100 of those countries that have the largest electricity generation in absolute terms in 2014. Since about 2/3 of all coal produced has been used in electricity generation, the thesis argues that it is appropriate to use only these 100 countries without expanding the analysis to further, smaller countries. Furthermore, this method could be further legitimized by the fact that the size of the electricity generation sector is generally a good indicator for the size of the economy, therefore considering only the 100 largest countries in this respect allows us to draw conclusions based on those countries where most of the power generation happens anyways and therefore likely having a larger global impact as well. This dataset was used to provide for relative comparisons, and is the basis for all calculations when coal usage, imports and production is described as a percentage of total primary energy supply (TPES). In addition for coal data for these 100 countries, the thesis also made use of annual natural gas production data, annual natural gas imports and the composition of sources of the electricity supply per year for the same 100 countries that produced electricity in the greatest amounts in 2014. The source of this data was also the world energy balances from the International Energy Agency (2017b).

The TPES values themselves have been sourced from a third dataset that is independent from coal data, but also published by the International Energy Agency (2016c) as part of the CO_2 Highlights, providing information on primary energy supply for all countries in the world from 1960 to 2014.

3.2 Time-series analysis at the decadal level

To reach the first two objectives of the thesis, the second dataset has been divided into four equally long time periods. The periods are 1974-84, 1984-94, 1994-2004, and 2004-2014. Even if the ranges include 11 years, they register change over 10 years; the first year of each period is seen as a base year, relative to which the change occurs over the remaining 10 years, so there is not an overlap between periods. This decadal division has been used throughout the analysis of the thesis, in answering all four objectives of the thesis, however, is most important in addressing the first two objectives.

The decision to carry out the analysis based on decadal intervals has some significant implications which are important to reflect on. The shorter the selected time intervals, the more easily could the analysis identify potential explanatory variables in all coal sectors, therefore the decadal interval level could be interpreted as rather long time series whereby small fluctuations are not effectively captured. While this may hold true, for the purposes of the analysis the thesis argues that decadal intervals are indeed appropriate for the following reasons. As the thesis attempts to provide a global overview of some potential factors that are associated with shrinking coal industries, longer observational time periods do not capture some of the fluctuations that shorter time periods would have. Since for instance in electricity generation, demand must always equal supply, short term weather or climatic effects could indeed drive coal fired electricity generation into negative or positive directions, an act that would merely be a response of the system to changing conditions, not a change within the system that this thesis is determined to identify. As it has been shown in the literature review, energy systems often have a large degree of resilience, hence any major changes that truly have an effect on energy systems are better observed at longer time intervals, for which the thesis considers decadal intervals to be appropriate.

In identifying the countries that significantly and persistently reduced either coal production or use in electricity generation, the thesis used the following cut-off criteria. First of all, the thesis defines a significant decline in coal use in electricity generation or production in absolute terms. The rationale for this is to filter out countries where coal production or use in electricity generation was insignificant from a global perspective, and thereby small changes in these countries do not affect the global carbon-dioxide emissions from the coal sector.

For coal production, a country needed to start the decade with at least 1.300 ktoe of coal production, below which the thesis did not consider the country as one where a substantial decrease in domestic coal mining could happen. Also, if the observed decrease at the decadal level was less than 10% in absolute terms, the thesis did not consider it as a case of decline, as it is arguable that in 10 years coal production may change by this much without any significant and long-lasting implications with regards to the future of the industry. The reasons behind choosing 1.300 ktoe as the cut-off point for domestic coal production are rooted in the cut-off criteria for coal use in electricity generation, which is explained below.

For coal use in electricity production, a country needed to start the decade with 1.000 ktoe in electricity generation, below which the thesis did not consider the country. 1.000 ktoe is about the amount of coal that would be needed to run a ~500 MW power plant at 80% capacity for a year at an efficiency of 30%, which resonates well with the global average efficiency of coal fired power plants. The cut-off criteria for a decline in domestic coal production is rooted in the cut-off criteria for electricity generation as arguably if a country extracts 1.000 ktoe per year for electricity generation, that leaves room for a further 300 ktoe output per year, to be used in the industrial or household sectors. 500 MW is a large enough power plant that could already have significance at the country level, even if there was only one coal fired unit operating in a country. Since at the global level 2/3 of the produced coal is used for electricity (Figure 8), the thesis considers the 1.000 ktoe per year coal use in electricity generation as an adequate threshold for electricity production. Furthermore, similarly to domestic coal production, the thesis did not consider periods where the absolute change at the decadal level was less than 10% as cases of decline of coal use in electricity production. It is important to mention that as opposed to domestic coal production, the thesis considered it important to strengthen the evidence for the decline of coal use in electricity generation provided by the absolute terms. Therefore, the analysis will only consider a decrease in coal fired generation as significant, if the decline can be observed both in terms of relative and absolute terms as well. The reason for this double check is that coal use in electricity generation may show a decline in the absolute terms, however, if simultaneously the total electricity supply is decreasing as well due to for instance energy efficiency, then coal may stagnate or increase in relative terms, thereby its significance within the system may have not at all changed.

Finally, the thesis defines a persistent decrease in domestic coal production and use in electricity generation if the country experienced a negative trend in at least two consecutive decadal intervals in 1975-2014. Arguably, any system-level changes in coal use and production may only prove valuable to the global environment, if it initiates changes that are not easily reversible, hence the criteria for at least two consecutive decades of decline. The thesis argues that with the above described cut-off definitions and filters, changes can be viewed as a firm enough evidence that it is not only some short-term shock that the industry is facing but rather the effects of long term structural changes. The cut-off criteria are summarised in Table 2.

Table 2: The cut-off criteria and definitions for significant and persistent declines in coal production or use in electricity generation

Terms	Criteria
Coal production	at least 1.300 ktoe in base year
	above 10% decline in absolute terms
Coal use in electricity generation	at least 1.000 ktoe in base year
	above 10% decline in absolute terms
	both absolute and relative measure taken into consideration
Significant decrease	at least once in non-consecutive decades
Persistent decrease	at least twice in consecutive decades

3.3 Medium-n analysis and deductive hypothesis forming

To achieve the last two objectives of the thesis, it uses a medium-n analysis, throughout which the hypotheses identified through the literature are tested. Medium-n analysis is defined as a technique that aims to explore the diversity, the simultaneous existence of similarities and differences (Ragin 2011) in cases when the number of observations lie between 40 and 50 cases (Rihoux 2006). Medium-n analysis is appropriate to be used in the thesis as there are a limited number of countries in the world, which have been further narrowed down to those 100 countries that produced electricity in the greatest absolute terms in 2014, but as the analysis will show, the number of countries are further reduced in the process of data cleaning to the levels appropriate for medium-n analyses.

In further answering the last two objectives of the thesis, the thesis uses deductive hypotheses based on the literature, which are then tested. The literature review identified potential explanations why countries decrease domestic coal production or usage in coal fired power generation. These then have been transformed into hypotheses, arguing that those conditions that characterised a decrease in coal production or usage in power generation are not specific to those specific countries, but can also be observed in other countries. To test the hypotheses the thesis uses the variables listed in Table 3 for each specific hypothesis.

The first hypothesis is that decreasing domestic coal mining is negatively associated with the imports of coal and natural gas. This is tested by looking at the change in coal and natural gas imports relative to the change in domestic coal production over the decade, both being expressed as a percentage of TPES. Consider the following example to illustrate the way the variables work:

in 1975 country A produced 10 ktoe of coal, while in 1984 it produced 5 ktoe, accounting for a 50% absolute decline. However, the thesis expresses the change in coal production relative to the TPES of the country of the base year of the decade, which was chosen to be a year before the beginning of the observations, therefore in this case 1974. So if country A had a TPES of 20 ktoe in 1974, in which domestic coal production declined from 10 ktoe in 1975 to 5 ktoe in 1984, then the change in coal production relative to the TPES of the country was -25% in the period 1974 to 1984. By utilising this method, the thesis considers decreases in relation to the sizes of the systems in which the decreased happened in. Also, by measuring the change in relation to the TPES of a country, countries become comparable to each other, thereby allowing to draw conclusions based on comparisons.

To find out whether the production of other domestic fossil fuels correlates with decline in coal mining, the thesis considers the change in domestic natural gas production over the decade and expressed as a percentage change in the TPES, which is then correlated to the change in domestic coal production over the decade relative to the percentage change in the TPES in the base year.

The final hypothesis for a decrease in domestic coal mining is the prevalence of underground mining, which is being tested by using a proxy variable, which is the percentage of brown coal production in the middle of the respective decade compared to the change in overall coal production relative to the TPES. It is arguable that brown coal is barely mined in deep shaft mines, so if there is a decrease or increase in domestic brown coal mining, it is likely that the open-pit mining output is changing accordingly, thereby being a proxy variable for the prevalence of underground mining.

The hypotheses for the reasons to decrease coal usage in electricity generation are tested with the following hypotheses. First of all, the thesis argues that coal based generation may decline as the domestically mined coal becomes less available, which is tested by looking at the change in coal based generation relative to total electricity supply, measured against the change in domestic coal production relative to the TPES. Secondly, the thesis also argues that the availability of nuclear power serves as a reason for the declined use of coal in power generation. This hypothesis is tested by looking at the change in nuclear power generation relative to total electricity supply, measured against the change in coal fired generation relative to total electricity supply. Thirdly, the thesis argues that the increased availability of other fossil fuels in the generation portfolio is also associated with a decreased use of coal in power generation. This hypothesis is tested by looking at the change in other fossil fuels in the generation portfolio relative to the total electricity supply, measured against the change in coal fired generation relative to total electricity supply.

Table 3: Hypotheses for decrease in domestic coal mining and use in electricity generation and their associated variables

Hypothesis		Explanatory Variable
Coal mining decreases because of …	availability of other domestic fossil fuel resources	Change in domestic natural gas production relative to change in domestic coal production, expressed as % of TPES
	availability of imports of coal and natural gas	Change in coal and natural gas imports relative to change in domestic coal production, expressed as % of TPES
	prevalence of underground mining	% of brown coal in total coal production
Coal use in electricity generation decreases because of …	decline in domestic coal mining	Change in coal based generation relative to total electricity supply, compared to change in domestic coal production, relative to TPES
	availability of nuclear power	Change in nuclear power generation, relative to total electricity supply compared to change in coal fired generation relative to total electricity supply
	availability of other fossil fuels in the generation portfolio	Change in other fossil (oil, gas), fuel based generation, relative to total electricity supply, compared to change in coal fired generation relative to total electricity supply

Before the thesis turns to the results section, it considers it important to state that the thesis is primarily concerned with correlations and not necessarily causations. As through the literature review the thesis has already shown, analyses of decreased coal reliance are widely available at the national level, however, studies are lacking that target the question from a holistic point of view. As the thesis is aiming to fill this gap in knowledge, as a first step it will primarily look at the conditions which commonly characterised a decline in domestic coal production or use in electricity generation, rather than the conditions that led to the decrease to arise in the first place.

In the results section, the thesis will employ a 6-step process that will be identical for all hypotheses to be tested, the focus of which is the Pearson Product-Moment Correlation Coefficient (*r*). This method is used to test for the existence of linear relationships between two sets of data that are interval or ratio level in nature and is generally the most often used method to test for correlation (Paler-Calmorin and Calmorin 1997). First, the thesis will spell out the null hypothesis, and the alternative hypothesis based on the literature review. The null hypothesis generally states that there is no relationship between the two considered sets of variables, whereas the alternative hypothesis formulates that there is a significant negative or positive correlation between the two sets of variables at hand. The significance of the correlation is tested in the following way. First of all, the thesis uses an alpha level (α) of 0,05 consistently, which determines that there is a 5 to 100 chance of making a Type I error, that is, rejecting a true null hypothesis. While a 5% probability of making an incorrect conclusion might be high, setting the alpha level at 0,05 has the advantage of balancing between Type I and Type II errors. Type II errors are cases when the researcher fails to reject a false null hypothesis.

After obtaining the *r*-values using the regression tools of Microsoft Excel, the thesis determines the degrees of freedom for the given dataset, which equals the number of observations subtracting two. Having obtained the *r*-values and taking their absolute value ($|r|$) and the degrees of freedom associated with each analysis, the critical level of *r* can be determined from the Pearson's *r* tables that match each degree of freedom with the critical *r*-value. An *r*-value of -1 indicates a perfect negative correlation, while an *r*-value of 1 indicates a perfect positive correlation. If the absolute value of the obtained *r*-value is greater than the critical *r*-value associated with the degrees of freedom of a one-tailed analysis at an alpha level of 0,05, then a significant correlation can be recorded. In addition to these statistics, the thesis will also report on the R^2-values, which can range from 0 to 1 and is obtained by squaring the *r*-values. R^2-values are a useful way to quickly and effectively measure the strength of the association between two variables, without having regard to the direction of that relationship. An R^2-value of 1 indicates a perfect correlation, while a value of 0 indicates no relationship at all.

Having determined the critical *r*-value level that is associated with the degrees of freedom of the analysis, the thesis formulates the decision rule for rejecting the null hypothesis. In doing so, the thesis states clearly the level and sign of the *r*-value that is expecting to be obtained for a significant negative or positive correlation to be found. In the final step of the hypothesis testing, the thesis clearly states whether the null hypothesis can be rejected or failed to be rejected. In testing some hypotheses, the thesis will run a number of different correlations. In these cases, the thesis may not go into the step-by-step breakdown of each individual analysis, and may only report that information that is relevant considering the primary aims and objectives of the thesis.

4 Global and regional trends in coal production and use[1]

This chapter introduces coal as an energy resource and its significance, both past and present in the global economy. Without going into the finer details, the chapter aims to provide a historical background to coal mining and utilisation, thereby framing the global coal mining and electricity generation trend in 1975-2014. The thesis will introduce the trends in historical coal mining, before 1975. Subsequently, the chapter will discuss the global trends in coal production and use in electricity generation from 1975 to 2014.

For the purposes of this preliminary analysis the report aggregates 1975-2014 coal data based on the 11-region categorisation in the Global Energy Assessment (International Institute for Applied Systems Analysis 2012) (Figure 14). The data that is used here is sourced from the International Energy Agency (2017b) for which chapter 3.1 of the methodology section gave a more detailed introduction to.

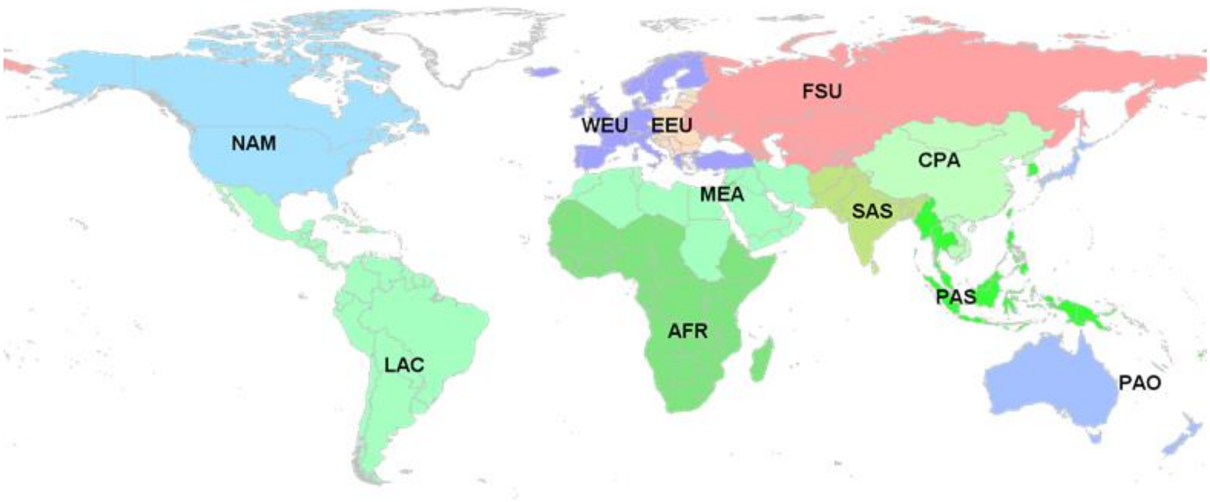

Figure 14: Regions used in the analysis (International Institute for Applied Systems Analysis 2012)

4.1 Coal mining trends before 1975

The early years of coal mining that was carried out already at the industrial level were characterised by a long-lasting dominance of the United Kingdom. Smil (2010) notes that in 1800 the country already produced 9 million tons of coal, while the second largest producer at the time only produced 100.000 tons. At the same time, other countries that have been large producers in the 20th century only started up large scale mining around this time, such as France Germany and

[1] Parts of this chapter have been submitted by the author as an assignment to the Sustainable Energy Transitions course in the Winter term of 2017 at the Central European University for fulfilling the requirements for obtaining the MSc in Environmental Sciences and Policy.

Belgium, but the scale of mining was not comparable to the UK (Smil 2010). Britain remained the number one coal producer well into the 19th century, as even in 1870 it was producing 50% of all coal worldwide, only to be surpassed by the United States at the turn of the century (Smil 2010).

Smil (2010) also points out that three large trends marked the global coal production of the 20th century. The first was the continuous decline of its relative importance as oil has started to gain share in global primary energy supply. Secondly in absolute terms, the industry was growing rapidly. Third the industry transformed from being highly labour intensive to highly mechanized. Ever greater amounts of lower grade coal were extracted in the 20th century, so open-pit mining started to become ever more important. However, in the middle of the century most coal was still mined in underground mines, with more and more mechanised techniques. A notable exception to the latter trend was China, where the industry was still dominated by a large number of small mines, relying on manpower rather than machinery. By the second part of the century though, the global distribution of coal mining started to shift: UK production first plateaued then went into a decline, whereas the USSR and China started to mine in ever greater quantities (Figure 15).

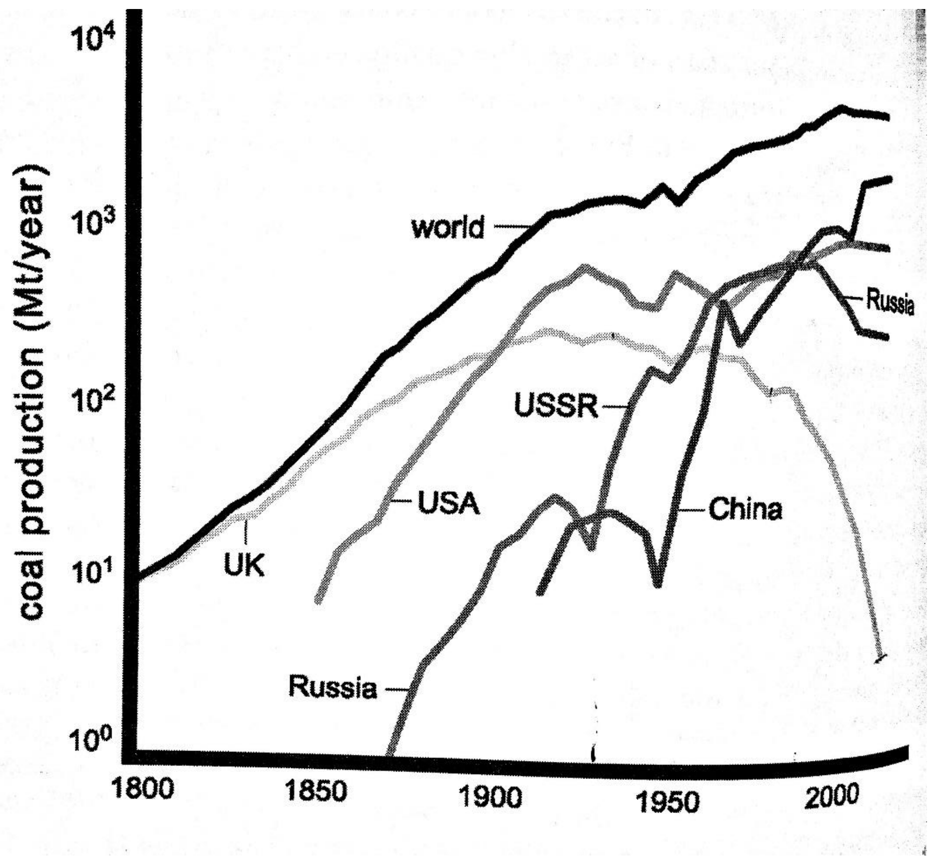

Figure 15: Coal production 1810-2010 (Smil 2010)

4.2 Global coal mining trends 1975-2014

Global coal mining is dominated by two regions, North America (NAM) and Centrally Planned Asia (CPA) (Figure 16). While in 1975, most coal was produced in North America, Centrally Planned Asia was producing at the level of Western and Eastern Europe. Among these four regions, only Centrally Planned Asia and North America managed to increase coal production in the observed time period. However, in North America coal mining plateaued between 500 and 600 mtoe for a long time, ultimately decreasing, starting from the second part of the first decade of the new millennium. On the contrary, coal mining did not plateau in Centrally Planned Asia, in fact a surge in mining happened at the turn of the millennium, when the region has already overtaken North America as the largest coal producer of the world. Despite the historically leading position of North America, 34% of all coal in 1975-2014 was produced in Centrally Planned Asia, while only 22% in North America. Although the overall absolute share of other regions are dwarfed by these large numbers, it is important that other regions are also increasing coal production in recent years, though not at such an incredible rate as Centrally Planned Asia. The most important regions in this case are Pacific OECD, South Asia and Other Pacific Asia, where coal mining has been continuously increasing in recent years. In fact, when considering the change in coal production compared to the base year in 1975, it is Other Pacific Asia that underwent the biggest increase in this regard (Figure 17), even the second placed Latin America and the Caribbean only increased production by only a third compared to that of Other Pacific Asia. The significance of this is that Asian regions in general are considered to be the next major driver for global coal production, as some countries in these regions, such as India in South Asia are only about to increase domestic output significantly (Cornot-Gandolphe 2016).

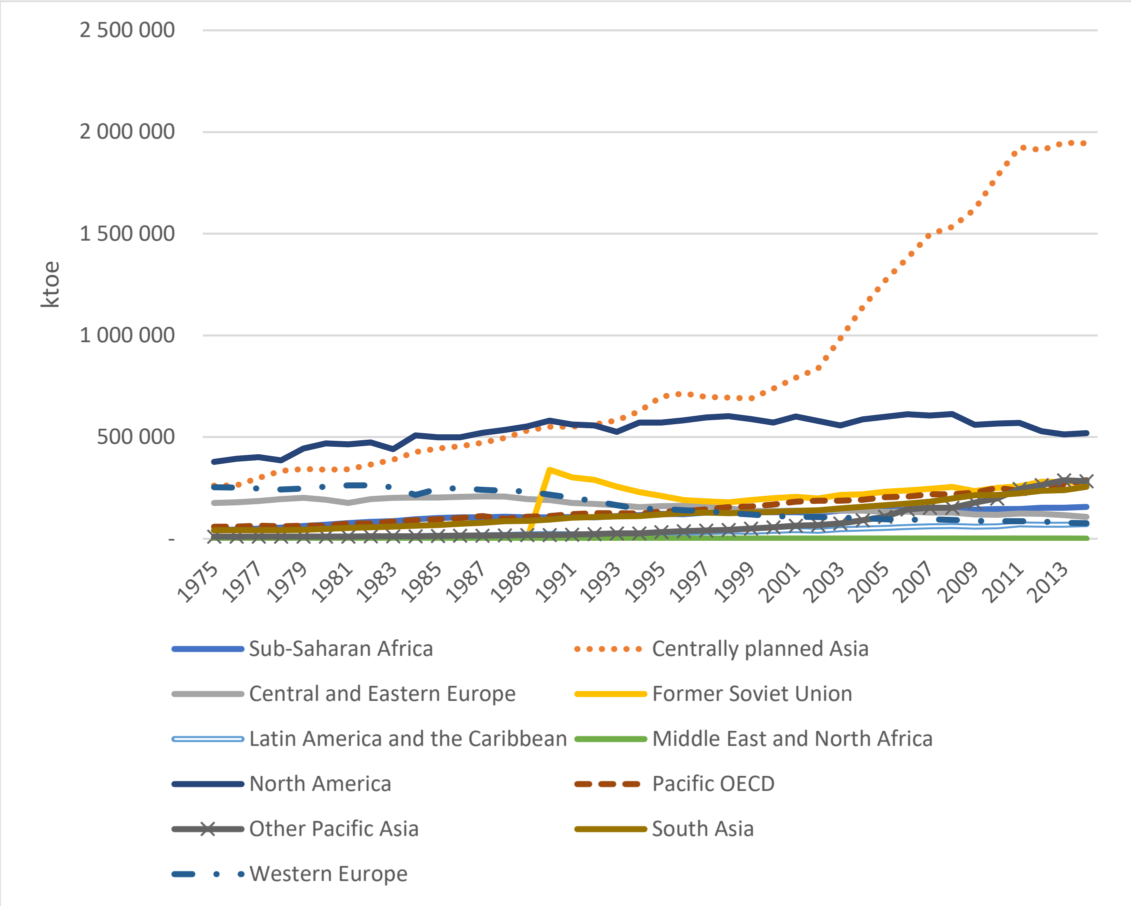

Figure 16: Coal mining by region 1975-2014 (International Energy Agency 2017b)

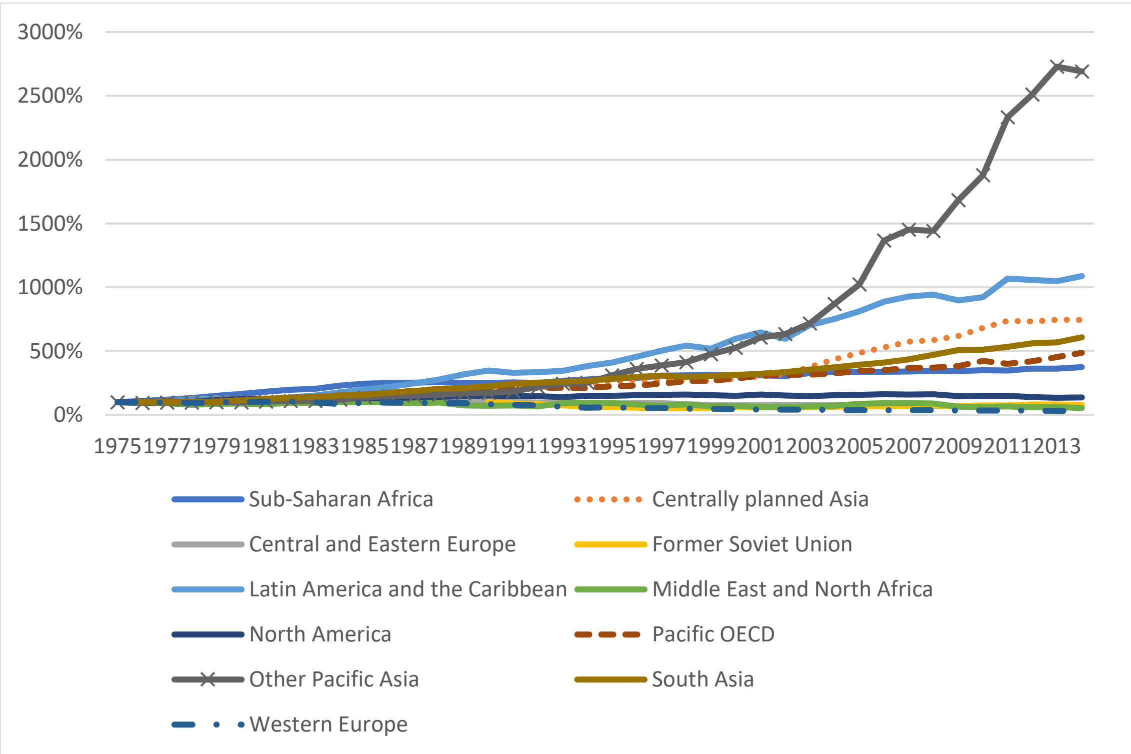

Figure 17: Change in global coal production at the regional level 1975-2014 (International Energy Agency 2017b)

4.3 Global coal trade trends 1975-2014

Coal is not an intensively traded commodity, currently 20% of the annually produced coal is imported into another country, yet the production to import ratio was at its maximum in 2015.

The shares of imports among the regions is relatively evenly distributed, especially if compared to the shares of coal production. In 2015, Other Pacific Asia imported 20,86% of the coal, followed by Western Europe at 20,33%. These two regions are followed by CPA, South Asia and Pacific OECD, having a share between 16-15% of the global coal imports. The remaining 6 regions accounted for 12,63% of the coal imports in total (Figure 18).

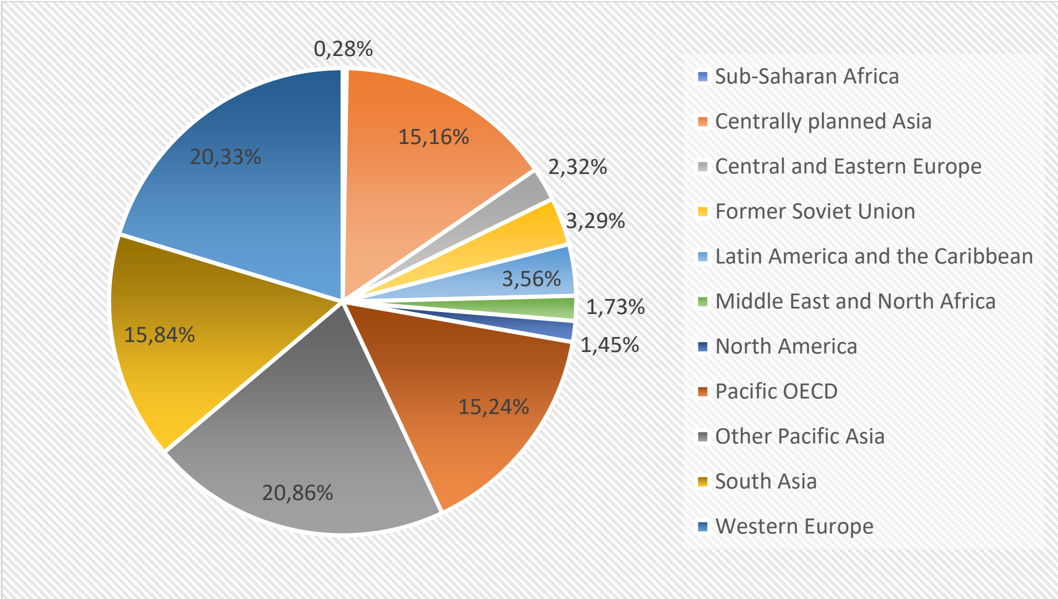

Figure 18: Shares of global coal imports by region in 2015 (International Energy Agency 2017b)

At the historical level, the below graph indicates how global coal imports evolved over time (Figure 19). Coal imports over the entire period have been largest in Western Europe. This indicates that while these countries might be the ones that reduced coal production, their coal use in electricity may not have decreased at the same time. The second most important coal import regions are all coming from the Asian continent or the Pacific region overall. Historically Centrally Planned Asia has not been a major coal importer, yet it showed the largest increase in coal imports that have been recorded in the time period of consideration. Though this surge in coal imports does not seem to last long, as already in 2014 and 2015 as well, coal imports have markedly decreased as the industry in China entered into a recession; the large stock-piling of coal lead to an oversupply and overall demand growth has first slowed down than decreased (Wu *et al.* 2017). A similarly marked, but increase in coal imports is witnessed in South Asia, India being an ever larger coal importer, while other Pacific Asia and Pacific OECD, especially Japan in the latter region, have remained strong coal importers throughout 1975-2014. All other regions showed rather stable import levels through recent history, perhaps with the exception of the Former Soviet Union just after the USSR dissolved, and North America from the beginning of the current decade. In both cases coal imports dropped markedly in a period of 4-6 years.

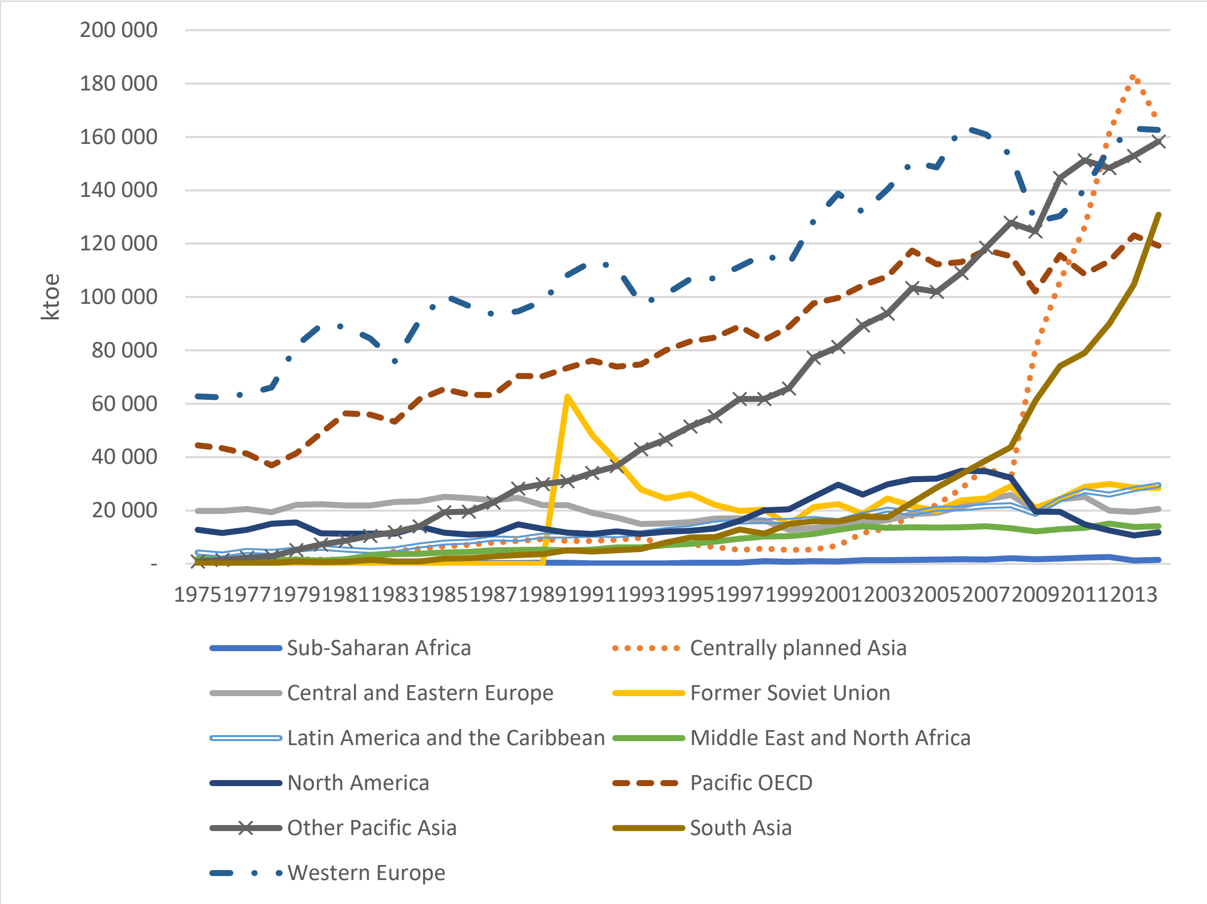

Figure 19: Coal imports by region 1975-2014 (International Energy Agency 2017b)

4.4 Is global coal trade or global coal production growing faster?

The dominance of NAM and CPA in global coal production is unquestionable, however, their share in imports despite being large is not as significant, highlighting the reliance of these regions on their own reserves. Therefore, it is worth to ask that if one disregards these two regions, how do the dynamics of coal production and imports change? If the surge in global coal production is truly associated only with the mining decisions of these two regions, then the number of actors involved in putting the global energy sector onto a more sustainable path reduces to two, however, if the opposite is true, then the world faces much greater complexity in solving this issue. Also, by identifying whether global coal production or trade is growing merely as a result of its largest players is also important, as in that case the conclusions of the thesis will only be applicable to a handful of countries, whereas if the opposite is true, a large number of smaller countries could also benefit from the findings of the thesis, looking to decrease their reliance on coal.

When looking at global coal production and imports from 1975-2014, three phases within the data can be discovered. From 1975 to 1990 global coal production rose faster than imports, however, the rate of change in global coal production changed in 1990 and approached the rate of change in global coal imports (Figure 20). The shock in 1990 that has brought about the decrease in global coal production is most likely the fall of the USSR, after which many countries that belonged to the communist block decreased coal production. The lack of a significant diversion between the rate of change in coal production and imports ended in 2003, from which the rate of coal production significantly outpaces coal imports. 2003 being the turning point corresponds to the large increase in coal production in Centrally Planned Asia as shown in Figure 16.

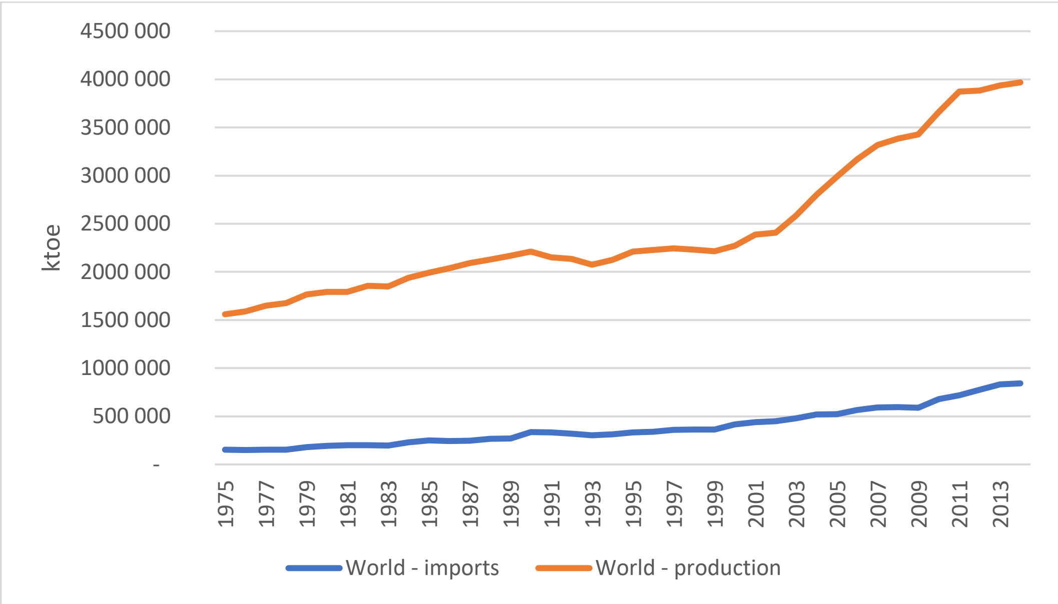

Figure 20: Global coal production and imports 1975-2014 ((International Energy Agency 2017b))

Removing North America and Centrally Planned Asia from the dataset changes the picture of global coal production and imports (Figure 21). First of all, coal production is much lower: the current level does not even reach 2 million ktoe, which was globally achieved before 1985. Secondly, coal production and imports from 1975-1985 were in line with each other, after which a decline in production was experienced that lasted until 1995 (most likely due to decline of coal use in former socialist countries of Eastern Europe and former USSR), however, this decline in production was not followed by a decline in imports. From 1995 onwards the two indicators started to converge again, with the past 10 years being characterized by production increases that outpaced imports.

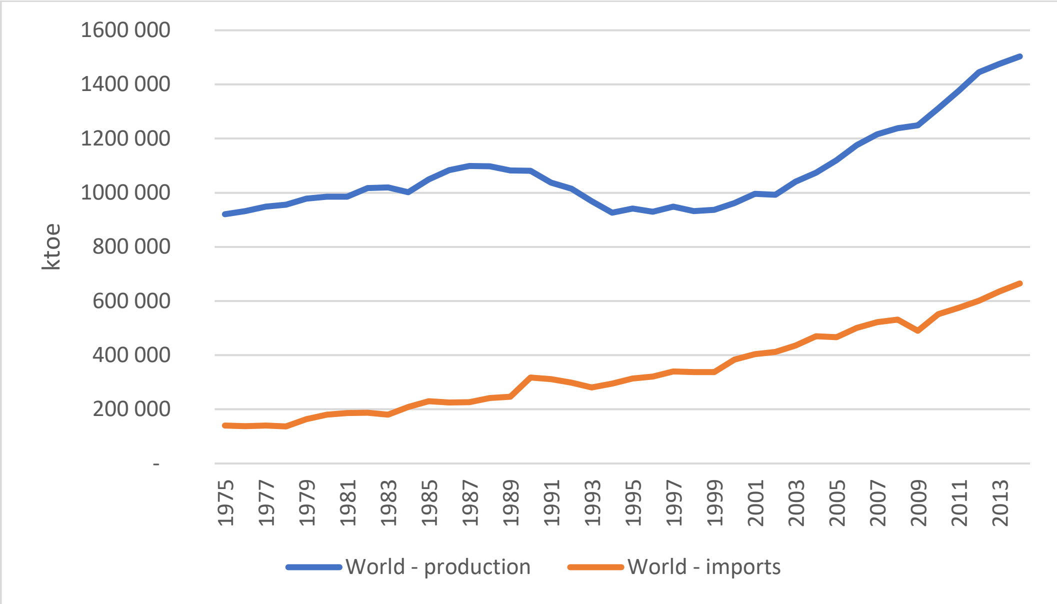

Figure 21: Global coal production and imports excluding Centrally Planned Asia and North America ((International Energy Agency 2017b))

In order to provide a more quantitative assessment of the rate of change of coal production and imports, the thesis considered the most recent time period only, looking at 2001-2015 to determine whether coal imports or coal production have been growing faster.

Taking all regions into consideration, the average growth rate of global col production was 122 mtoe per year in the period of 2001-2015, whilst imports only grew at 30 mtoe per year in the same period (Figure 22), suggesting a four times more intensive growth in production than imports.

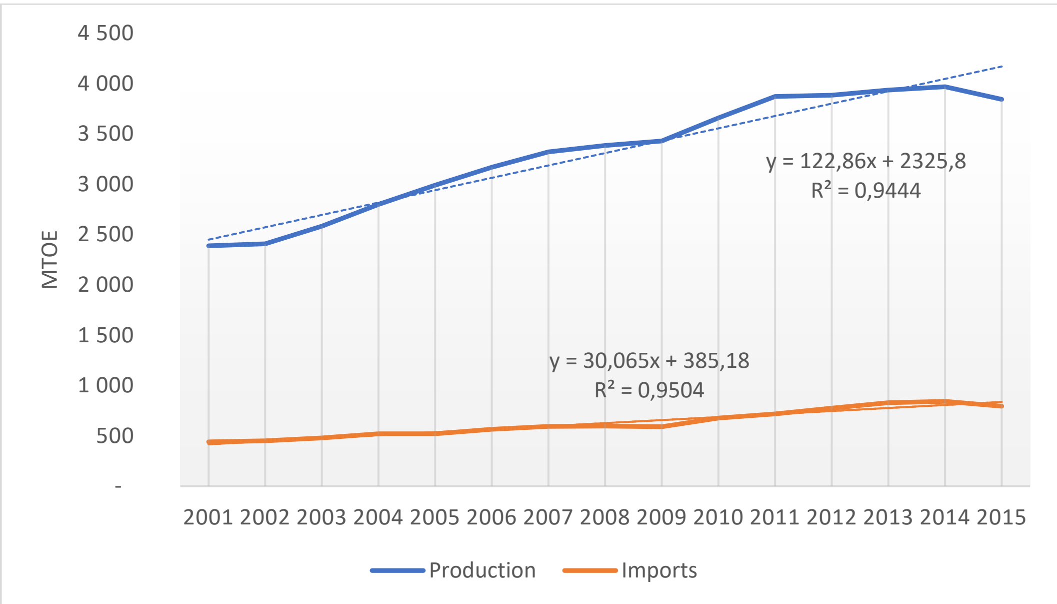

Figure 22: Rate of change in global coal imports and exports 2001-2015

The same holds true in 2001-2015, even if the two largest coal producing regions are disregarded. In that case, production grows at 40 mtoe per year, whilst imports escalated by 18,74 mtoe year-on-year (Figure 23). Although removing CPA and NAM did slow down the production rate of coal, nevertheless production still increased twice as fast as imports.

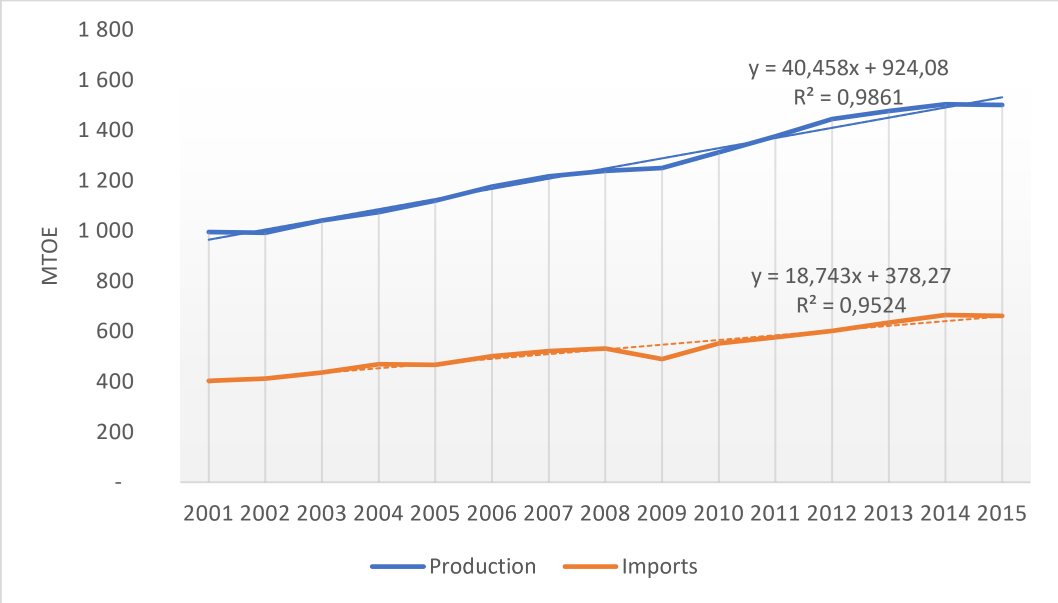

Figure 23: Rate of change in world coal production and imports, Centrally Planned Asia and North America removed

The higher growth rates in coal production compared to imports without Centrally Planned Asia and North America suggest that it is not only these two regions that drive the surge in global coal production, but other regions that overall do not have a large share in worldwide production are increasing their mining output as well and they are likely not to import most of the coal, but produce it themselves. From a transition management perspective, this increases the number of actors that are required for a shift in the global energy mix, and may also suggest that technological advancements, such as carbon capture and storage, that have the capacity to make coal usage more sustainable in the long term will need to have a role to play, if the commodity is to be widely used in the future as well. For the purposes of the thesis, these findings suggest that indeed the conditions that characterise decreased coal production and use in electricity generation are not only applicable to a handful of large coal consuming countries, but in fact a large number of small producers and users could indeed use the findings of the thesis if they wish to decrease coal use in electricity generation or production.

4.5 Global coal use in electricity generation 1975-2014

The North American region used the most coal in electricity generation, namely 16,4 billion toe in the period of 1975-2014 (increasing by 72% in that period) (Figure 24). Centrally Planned Asia used

12,7 billion toe for the same period but the growth of use was much bigger (about 230 times between 1975-2014 or almost doubling on average year-on-year). Despite the fact these two regions used the most of product, the change in coal usage in power generation was the greatest in Other Pacific Asia, only to be seconded by the Middle East and North Africa, Latin America and the Caribbean, South Asia and the previously mentioned Centrally Planned Asia (Figure 25). Within this period Centrally Planned Asia and North America accounted for 62% of all the coal use for electricity generation in the world. The fact that the growth rate of Centrally Planned Asia quickly outpaced that of North America in the absolute usage of the commodity shows the velocity at which rapidly industrialising nations or regions may adopt coal usage at large scales, and therefore the landscape of coal usage in electricity generation can indeed change sometimes rapidly, as it happened with North America and Centrally Planned Asia as well, as the latter quickly overtook the former in the observed time period.

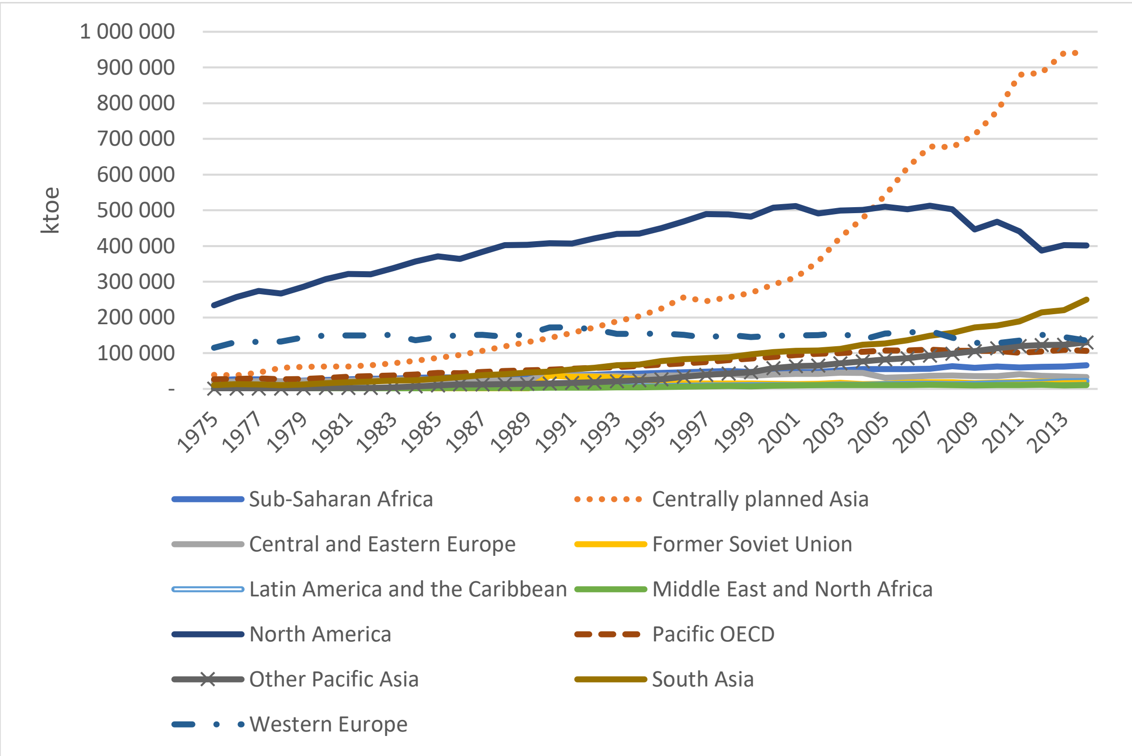

Figure 24: Coal use in electricity generation by region 1975-2014 (International Energy Agency 2017b)

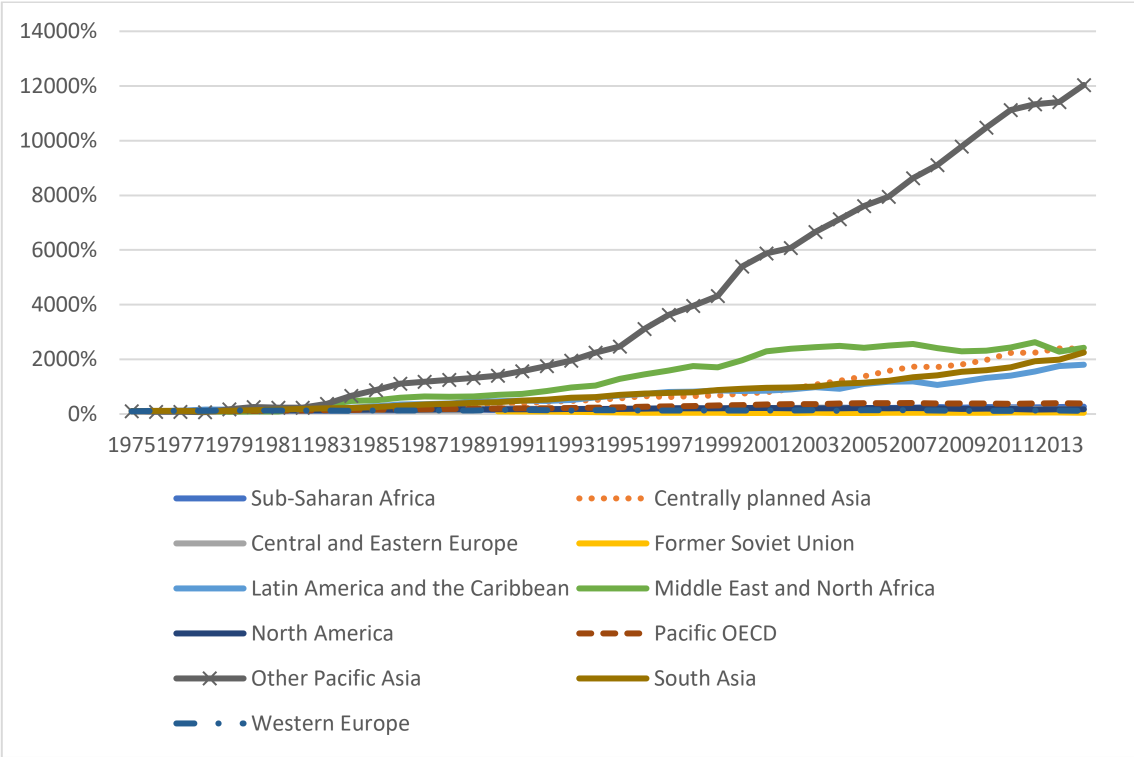

Figure 25: Change in coal use in electricity productions by world regions 1975-2014 (International Energy Agency 2017b)

Such movements across the sample are not uncommon, the landscape of coal usage in electricity production is remarkably different in 2014, then it was in 1975. When ranking regions based on their occupied position in the share of coal fired electricity generation, one can identify those regions that have decreased or increased their use the most in comparison to other regions. Of all 11 regions considered, seven of them had lower ranks in 2014 than in 1975. Western Europe, Pacific OECD, Central and Eastern Europe and Sub-Saharan Africa had all lower ranks in consumption levels in 2014 than in 1975; these regions lost two rankings in the observed time period (Table 4). Besides these two regions, Latin America, the Middle East and North America also had lower rankings, by losing one position each on the list of coal-fired electricity generation of the regions. On the other end of the spectrum, there are the rapidly industrialising regions, such as South Asia and Other Pacific Asia that each gained 4 positions in the rankings, but Centrally Planned Asia was also enriched by two positions. The thesis considers that it is likely that those countries are the ones that managed to decrease coal use in electricity production significantly and permanently enough that are found in the regions that showed a marked decline in the observed time period as well. Of course there could be outliers, where national trends go against regional trends, however, drivers that resulted in the phase-out of coal from electricity generation may be just as well present at the regional as at the national level.

Table 4: Ranking of regions based on coal usage in 1975 and 2014

	Rank 1975	Rank 2014	Change
Sub-Saharan Africa	5	7	-2
Centrally planned Asia	3	1	2
Central and Eastern Europe	6	8	-2
Former Soviet Union	11	10	1
Latin America and the Caribbean	8	9	-1
Middle East and North Africa	10	11	-1
North America	1	2	-1
Pacific OECD	4	6	-2
Other Pacific Asia	9	5	4
South Asia	7	3	4
Western Europe	2	4	-2

4.6 The future of coal

In 2005, the IPCC reported that although no single technology will provide the ultimate resolution to mitigate increasing greenhouse gas emissions, nevertheless carbon capture and storage (CCS), the geological storage of carbon will have an important role to play (Intergovernmental Panel on Climate Change 2005). Jewell *et al.* (2013) note that in a business-as-usual scenario, where carbon reduction efforts are not undertaken, global coal trade will intensify, however, in case there is going to be a push for low-carbon targets, global coal use is only compatible with low-carbon targets in the presence of CCS technologies as well. Despite the need for a mature and functioning CCS technology, a current assessment by Gaede and Meadowcroft (2016) shows that even the uptake of large-scale demonstration CCS projects is lagging behind and that only a handful of countries are capable of deploying such technologies even at the demonstrational level, although as the thesis showed it, it is a large number of smaller countries, not only the large producers that are increasing production in recent times. Consequently, despite the need for CCS technologies to be deployed at large scale in the near future, realising this is unlikely to happen. Therefore, the thesis argues that instead of the technological solution that CCS could provide to decrease carbon emissions from coal combustion, the focus should shift to other measures, perhaps even existing ones, that countries have already deployed to decrease their reliance on coal production or use in electricity generation.

5 Results

5.1 Countries that decreased domestic coal production

In the following two subchapters the thesis will present those countries that reduced coal production and electricity use according to the cut-off criteria presented in Table 2. First those countries are presented that experienced a significant decline according to the cut-off criteria. A significant decline is defined as one that meets the cut-off criteria but is only registered in one or multiple but non-consecutive time intervals. Second, those countries are presented that meet the cut-off criteria but experience the decline in consecutive time intervals. As a result, countries that both significantly and persistently reduced reliance on coal are considered to be a subset of those countries where only significant decline took place.

5.1.1 Countries with significant decreases

Table 5 below shows countries that experienced a significant decrease in their domestic coal output in the period of 1975 to 2014 in absolute terms. The values presented in Table 5 are the percentage changes in coal production in the first versus the last year in each decade under consideration. Altogether there are 15 such countries. Most of the occurrences of decrease happened in 2005-2014. It is important to emphasize that none of the countries that experienced a decline in coal output ceased coal production following the decline, in fact the majority of the countries that experienced the decline before 2005 in fact increased production following their period of downturn. The only exception to this observation is Slovakia, where production slowly decreased, but the production levels were below the set threshold in 2005-2014, and Slovakia is still producing some coal nowadays.

Venezuela decreased production by most, 83% in 2005-2014. The country's coal mining sector seems to have undergone a major boom and bust cycle: production levels were basically insignificant until 1987, at 45 ktoe in 1987, then production peaked at nearly 6.000 ktoe in 2001, maintaining high levels of production for 4 years, then the industry entered the phase of diminishing output. The decline seemed to have stopped in 2013, production levels have been stagnating near 800 ktoe in recent years. On the other end of the scale, Turkey and Mongolia decreased coal production by the least but still above the thresholds presented in Table 2, standing at 13% in both cases. Although both of the declining periods occurred in 1995-2004, however, the two countries exhibit very different patterns when it comes to the preceding time periods before the declining period. In Turkey, coal production has been slowly and steadily increasing up until the turn of the millennium, when production levels fell back from 14.000 ktoe to near 10.000 ktoe in 2005. Following this period, coal production rose quickly to 2011, from which output has been declining again in recent years. The case of Mongolia exhibits a different pattern than that of Turkey despite the same scale in output decline. Production levels have been stable at 2.000 ktoe until 2004, when output has started to increase significantly up until 2011 when it reached levels of 18.000 ktoe. Following the peak, coal production has started to dwindle, falling back to just over 14.000 ktoe in 2014.

Table 5: List of countries and time periods when countries significantly reduced coal production within at most one decade

	1975-1984	1985-1994	1995-2004	2005-2014
Brazil	248%	-43%	5%	22%
Bulgaria	19%	-5*%	-14%	23%
Canada	117%	17%	-21%	1%
Greece	88%	52%	14%	-25%
Mongolia	n/a	-7%*	-13%	261%
New Zealand	27%	35%	44%	-26%
Pakistan	29%	36%	19%	-24%
Serbia	n/a	n/a	5%	-23%
Thailand	451%	230%	9%	-24%
Slovakia	-1%*	-36%	-20%*	-9%*
Turkey	55%	13%	-13%	50%
Ukraine	n/a	n/a	-18%	-8%*
United States	31%	14%	5%	-14%
Venezuela	-23%*	10595%	66%	-83%
Zimbabwe	9%	60%	-31%	60%

*below 10% or 1.300 ktoe threshold

5.1.2 Countries with both significant and persistent decreases

There are altogether 11 countries that decreased domestic coal production both significantly and persistently (Table 6). Of these 11 countries, only Japan ceased production entirely post the declines, however, Belgium, France and South Korea only maintained coal production levels that were below the pre-defined 1.300 ktoe. Interestingly, there are a number of countries that are considered to be major coal producers even nowadays despite the fact that coal production has been declining continuously in these countries. One of the most notable examples is Poland, which has previously been the greatest exporter of coal in Europe, a title it does not carry anymore, yet Poland is still one of the largest producers of coal in Europe. The largest European producer of coal also experienced continuously declining production levels though, as output has been diminishing in Germany in the last 30 years. The case of the Czech Republic is similar as well:

although its historical significance as a coal producer cannot be compared to that of Poland, yet it has been a major user of the commodity, especially in its electricity generation, yet it has also been experiencing a dwindling coal mining industry.

It is notable that all countries that experienced a substantial and persistent decline in their output are now considered to be OECD countries, with the exception of Romania, however, arguably Romania's economic development is comparable for example to that of Poland. Furthermore, the majority of these countries are European and are basically neighbouring countries, it is only Slovakia that is missing from the list for a continuous region to be formed from the United Kingdom through the Czech Republic to reach Hungary and Romania. Only Japan and South Korea are not European states from the below list, however, the economic development of these countries are not only comparable to each other, but to some of the more developed European states as well. Therefore, an important finding is that so far it is only relatively well-developed countries economically that managed to both significantly and persistently reduce coal output.

Table 6: List of countries with significant and persistent declines in coal production

Country	1975-1984	1985-1994	1995-2004	2005-2014
Belgium	-23%	-93%	-69%*	-95%*
Czech Republic	6%	-32%	-10%	-28%
France	-28%	-46%	-91%	-51%*
Germany	1%	-44%	-26%	-22%
Hungary	8%	-46%	-33%	-9*%
Japan	-23%	-63%	-100%	ceased production
Poland	12%	-27%	-24%	-22%
Romania	52%	-24%	-20%	-23%
South Korea	14%	-69%	-42%	-38%*
Spain	93%	-20%	-36%	-74%
United Kingdom	-60%	-47%	-54%	-43%

*below 10% or 1,300 ktoe threshold

5.2 Countries that decreased coal-fired electricity generation

5.2.1 Countries with significant decreases

Based on the criteria described in section 3.2 (Table 2), the thesis identified the following countries, altogether 16, that decreased coal use in electricity generation significantly, therefore only in one or multiple, but non-consecutive time periods. The table below (Table 7) gives an overview of the decline in coal use in both absolute and relative terms, for all decadal intervals of considerations.

The Czech Republic and France stands out from all other countries, as these are the only two countries that experienced a decline in two decadal intervals, however, they cannot be considered as persistent decreases because the declines did not happen consecutively. In the case of the Czech Republic, although use declined in all periods in absolute terms except for 1975-1984, however, in 1995-2004 coal use in relative terms increased despite marginally falling absolute levels. Consequently, the thesis proposes that the overall decline over the four decades cannot be considered as persistent, as the decline was interrupted by a major increase in absolute terms, hence the decline was likely driven by factors affecting overall electricity supply, and not the coal sector specifically.

Besides the Czech Republic, France is the other country that experienced a significant decrease in its use of coal in electricity generation for two decades, although not consecutively. In 1985-1994 coal usage in absolute terms has decreased by 45%, which corresponded to a relative decrease of 10% in the same period. In the next ten years though, the use of coal rose again, with a 10% rise in absolute terms, which corresponded to a 1% increase in relative terms, hence the significance of coal in the national energy mix rose slightly in this period. In the most recent ten year period though, usage in absolute terms decreased majorly by 60%, which corresponded only to a 3% decline in relative terms, thereby suggesting the then already not that great significance of coal in the national electricity mix of France.

The 14 countries other than France and the Czech Republic experienced a declining trend in their usage of coal for electricity generation only in one of the decadal intervals. The average decrease in absolute terms was rather large, standing at 34%, however, the relative decline was accordingly smaller, standing at 9,31%. The largest absolute decline was achieved by New Zealand in 2005-2014, corresponding to a 75% decrease in coal use in electricity production (-6,65% in relative terms), while the largest relative diminishment was recorded for Ukraine in the period of 1995-2005, standing at -15,85% (-43% absolute decline). On the opposite side of the scale, the smallest absolute decline that still fit the qualifying criteria of the thesis was observed in Romania at 11% (-7% relative diminishment).

Of the 14 countries that experienced a decline only once in the observed period, the decline in 10 cases corresponds to the latest tie period of 2005-2014. Only Italy experienced a rather large decrease in absolute terms in 1985-1994, while Colombia, Ukraine and Zimbabwe all showed diminishing trends in 1995-2014. It is suggestive that 10 of the 14 countries that manifested a decline are OECD countries, and it was only OECD countries, with the exception of Romania, that managed to decrease coal use in electricity production in the most recent time period.

Table 7: Countries that substantially decreased coal use in electricity generation

Country	Product	1975-1984	1985-1994	1995-2004	2005-2014
Czech Republic	Electricity (absolute terms)	26%	-20%	-0,1%*	-22%
	Electricity (relative terms)	38%%	-15%	17%	-13%
France	Electricity (absolute terms)	28%	-45%	-10%	-60%
	Electricity (relative terms)	9%	-10%	1%	-3%
Australia	Electricity (absolute terms)	35%	34%	32%	-16%
	Electricity (relative terms)	50%	48%	26%	-12%
Austria	Electricity (absolute terms)	-10%*	-42%*	183%	-46%
	Electricity (relative terms)	4%	-2%	10%	-6%
Canada	Electricity (absolute terms)	134%	4%	14%	-36%
	Electricity (relative terms)	18%	1%	3%	-6%
Colombia	Electricity (absolute terms)	74%	31%	-56%	155%
	Electricity (relative terms)	7%	4%	-4%	11%
Greece	Electricity (absolute terms)	109%	56%	-4%*	-49%
	Electricity (relative terms)	62%	53%	14%	-16%
Israel	Electricity (absolute terms)	n/a	103%	90%	-12%
	Electricity (relative terms)	81%	69%	70%	-14%
Italy	Electricity (absolute terms)	310%	-26%	84%	-5%*
	Electricity (relative terms)	14%	-2%	10%	-1%
New Zealand	Electricity (absolute terms)	-2%*	-61%*	605%	-75%
	Electricity (relative terms)	-2%	-0,1%	12%	-7%%
Romania	Electricity (absolute terms)	n/a	n/a	75%	-11%
	Electricity (relative terms)	n/a	n/a	4%	-7%
Portugal	Electricity (absolute terms)	-83%*	1141%	11%	-21%
	Electricity (relative terms)	-2%	58%	10%	-6%
Spain	Electricity (absolute terms)	206%	18%	n/a	-43%
	Electricity (relative terms)	46%	11%	n/a	-13%
Ukraine	Electricity (absolute terms)	n/a	n/a	-43%	30%
	Electricity (relative terms)	n/a	n/a	-16%	14%
United States	Electricity (absolute terms)	49%	18%	11%	-21%
	Electricity (relative terms)	29%	14%	8%	-9%
Zimbabwe	Electricity (absolute terms)	70%	244%	-22%	12%
	Electricity (relative terms)	8%	58%	-13%	2%

*below 10% or 1.000 ktoe threshold

5.2.2 Countries with both significant and persistent decreases

Compared to the rather numerous countries that manifested a single or non-consecutive decades of declining coal burning in electricity production, the number of countries that managed to do this not only substantially but persistently as well is rather limited: only Belgium, Hungary, the United Kingdom and Denmark exhibited such patterns (Table 8). The United Kingdom is superior compared to the other three nations, as it exhibited declining patterns in all four-time intervals when observed in absolute terms, however, in relative terms coal use increased in 1985-1994 by almost 12%. Hungary is performing the second best in this aspect, as it manifested the declining trends over three decades persistently, even if both absolute and relative decreases were below 2% in 1995-2005. Belgium and Denmark exhibit similar patterns with regards to the timing of the decline, however, Belgium showed greater decreases in absolute terms, while in Denmark relative decreases were of greater magnitude.

The temporal distribution of the declining events and the characteristics of these countries are akin to those countries that only managed to decrease coal fired power generation in a single or non-consecutive periods. All countries experienced a decline in the last two time periods, with only the United Kingdom and Hungary experiencing declines earlier than this. Perhaps also importantly, all four countries that so far managed to substantially and significantly decrease coal use in power generation are OECD countries.

Table 8: List of countries that substantially and persistently reduced coal use in electricity generation

Country	Product	1975-1984	1985-1994	1995-2004	2005-2014
Belgium	Electricity (absolute terms)	19,02%	27,13%	-28,00%	-61,00%
	Electricity (relative terms)	16,88%	2,66%	-10,76%	-7,68%
Hungary	Electricity (absolute terms)	9,08%	-25,00%	-1,56%*	-14,00%
	Electricity (relative terms)	0,11%	-8,18%	-1,46%	-5,40%
United Kingdom	Electricity (absolute terms)	-29,00%	-17,00%	-10,00%	-29,00%
	Electricity (relative terms)	-7,63%	11,87%	-8,21%	-7,84%
Denmark	Electricity (absolute terms)	240%	22,08%	-31,74%	-28,44%
	Electricity (relative terms)	88,25%	41,96%	-40,90%	-20,26%

*below 10% or 1.000 ktoe threshold

5.3 Correlates of declining domestic coal production

5.3.1 Increasing coal and natural gas imports to decrease domestic coal production

To test the hypothesis whether an increase in natural gas and coal imports is associated with a decrease in domestic coal production, the thesis tested the correlation between changes in domestic coal production with changes in net natural gas and coal imports, all relative to the total primary energy supply.

As the first step, the data was cleaned by removing those countries and periods when coal production was not taking place. In this case, the explanatory dataset did not have to be cleaned, as all countries that were producing coal even at insignificant levels also had coal and natural gas imports in all time periods as well. After these data manipulations, there remained 234 data pairs within the dataset, providing the most numerous data pairs throughout the entire analysis.

First, the analysis was carried out considering all coal producing countries at once. The null hypothesis (H_0) for all interval periods is that there is not a relationship between the changes in domestic coal production and changes in natural gas and coal imports, therefore H_0 is that r=0. The alternative hypothesis (H_1) is that there is a significant negative correlation between changes in domestic coal production and changes domestic natural gas production in the same period, therefore H_1 is that $r \leq 0$. The level of significance, as discussed in the methodology is chosen to be 95%, therefore $\alpha = 0{,}05$. The degrees of freedom (df), and r-values for each decadal period are presented in Table 9. Considering the number of objects in the dataset and the derived df-values, the alternative hypotheses should be rejected for each decadal interval, if r fails to be larger than 0,195-0,231, depending on the decade and the number of countries associated with each period.

Considering all countries, the analysis reveals a generally significant and negative correlation between domestic coal production and coal and natural gas imports. Although in the case of 1974-1984 the null hypothesis cannot be rejected, in all other subsequent periods there is an inverse and significant relationship. This correlation is the strongest in 2004-2014, followed by 1984-1994, with relatively weak correlations in 1994-2004. In 1984-2014 therefore the thesis finds that the null hypotheses can be rejected in favour of the alternative, hence there is generally a significant and negative relationship between domestic coal production and coal and gas imports.

Table 9: Correlation statistics for domestic coal production and coal and natural gas imports worldwide

	1974-1984	**1984-1994**	**1994-2004**	**2004-2014**
df	50	51	64	61
r	- 0,12	- 0,51	- 0,26	- 0,62
R^2	0,01	0,26	0,07	0,39
Reject H_0 if $\lvert r \rvert$	≥ 0,231	≥ 0,211	≥ 0,195	≥ 0,195
H_0 is	failed to reject	rejected	rejected	rejected

To test further for this relationship, the thesis subdivided the countries into OECD and non-OECD nations, finding that overall the observed negative correlation in OECD countries is stronger than in non-OECD countries. Table 10 shows the correlation statistics for OECD countries, showing that the significance pattern is akin to that presented in Table 9, the null hypotheses can be rejected in all periods, except for 1974-1984. It is notable, that both the r and R^2 are higher in OECD countries compared to all countries, suggesting that the inverse relationship is stronger for domestic coal production and fossil imports, than if all countries are considered.

Table 10: Correlation statistics for domestic coal production and coal and natural gas imports in OECD countries

	1974-1984	1984-1994	1994-2004	2004-2014
df	25	26	27	25
r	- 0,21	- 0,59	- 0,39	- 0,62
R^2	0,04	0,34	0,16	0,39
Reject H_0 if $\|r\|$	≥ 0,323	≥ 0,317	≥ 0,311	≥ 0,323
H_0 is	failed to reject	rejected	rejected	rejected

The correlation in non-OECD countries is a mixed picture (Table 11). In the first period, the null hypothesis is failed to be rejected, just as in previous cases. In the second period, the null hypothesis is rejected in favour of the alternative, however, the R^2-value indicates a much lower explanatory power here than in OECD countries. In the third period, the null hypothesis is again failed to be rejected, only to be rejected in the fourth period, which also provides the largest R^2-value of all of the analysed time intervals. It is therefore fair to conclude that coal and gas imports in non-OECD countries show a lower degree of correlation overall compared to other countries, except for the latest time period where this relationship was the strongest.

Table 11: Correlation statistics for domestic coal production and coal and natural gas imports in non-OECD countries

	1974-1984	1984-1994	1994-2004	2004-2014
df	23	23	35	34
r	- 0,07	- 0,40	- 0,26	- 0,65
R^2	0,01	0,16	0,07	0,42
Reject H_0 if $\|r\|$	≥ 0,337	≥ 0,337	≥ 0,275	≥ 0,275
H_0 is	failed to reject	rejected	failed to reject	rejected

5.3.2 Increase in domestic natural gas production to decrease coal production

To test the hypothesis that an increase in domestic natural gas production leads to a decrease in domestic coal production, the thesis tested the correlation between changes in domestic coal production with changes in domestic natural gas production at the decadal level, relative to the total primary energy supply.

First, the datasets were cleaned. The starting list of the countries was again the 100 countries that produced electricity in the greatest quantities in 2014, and their coal and natural gas production relative to the TPES of the countries. First, those countries were removed from the dataset that did not produce coal at all in all periods, then also those time period-pairs were removed in which the country did not produce any of the commodity. The reason for this cleaning is the same as before, as those countries that did not produce any of the commodity are likely to have done so because of the absence of any kind of reserves. As a second step, the thesis further omitted those data point pairs as well, where the country did not produce any natural gas, for similar reasons as in the case of coal. With these changes in consideration, there were 201 data pairs left in the analysis.

The null hypothesis (H_0) for all interval periods is considered to be that there is no relationship between the changes in domestic coal production and changes in domestic natural gas production, therefore H_0 is that $r = 0$. The alternative hypothesis (H_1) is that there is a significant negative correlation between changes in domestic coal production and changes in domestic natural gas production in the same period, therefore H_1 is that $r \leq 0$. The level of significance, as discussed in the methodology is chosen to be 95%, therefore $\alpha = 0{,}05$. The degrees of freedom (df), and *r*-values for each decadal period are presented in Table 12. Considering the number of objects in the dataset and the derived df-values, the alternative hypotheses should be rejected for each decadal interval, if *r* fails to be larger than 0,211-0,257, depending on the decade.

As Table 12 shows, the analysis did not reveal any significant relationship between increasing domestic natural gas production and decreasing domestic coal production. Not only do the *r*-values indicate a slight positive relationship between the two variables, but most importantly, none of the correlations is significant, therefore the null hypotheses are failed to be rejected in all decadal interval periods.

Table 12: Correlation statistics for domestic coal and natural gas production

	1974-1984	1984-1994	1994-2004	2004-2014
df	40	44	54	55
r	-0,12	0,14	0,03	0,08
R^2	0,01	0,02	0,001	0,01
Reject H_0 if $\lvert r \rvert$	≥ 0,257	≥ 0,243	≥ 0,211	≥ 0,211
H_0 is	failed to reject	failed to reject	failed to reject	failed to reject

To find out whether there is a significant negative correlation between domestic coal and natural gas production, the thesis went further and carried out the analysis considering the division of OECD and non-OECD countries, however, the results suggest that there is not a significant negative correlation even with this division. The table below shows the *r* and R^2-values for OECD countries in the respective time periods; the null hypotheses and alpha levels were chosen to be the same as in the previous instances. Table 13 shows that despite the fact that in 1974-1984 and 1994-2004 there is a negative correlation between the two variables, however, the explanatory power of the correlation is extremely limited due to the low R^2-values and nor is the correlation significant, therefore the null hypotheses could not be rejected in any of the cases.

Table 13: Correlation statistics for domestic coal and natural gas production in OECD countries

	1974-1984	1984-1994	1994-2004	2004-2014
df	16	19	31	32
r	- 0,13	0,05	- 0,07	0,01
R^2	0,02	0,002	0,001	0,00004
Reject H_0 if |r|	≥ 0,4	≥ 0,369	≥ 0,275	≥ 0,275
H_0 is	failed to reject	failed to reject	failed to reject	failed to reject

The situation is highly similar in the case of non-OECD countries as well, however, in one instance there is a significant correlation between the two variables, although not of the expected direction (Table 14). In the case of non-OECD countries, there was only one instance, in 1974-1984 when the observed correlation was negative, however, not significant. There is a significant and positive correlation though in 1984-1994, but the null hypothesis cannot be rejected despite the significant relationship, as $r \geq 0$ as opposed to the set criteria of $r \leq 0$. Conclusively, in non-OECD countries a decrease in domestic coal production is not associated with an increase in domestic natural gas production, only in 1984-1994 is the relationship significant but positive, thus in this period an increase in domestic coal production was also associated with an increase in domestic natural gas production.

Table 14: Correlation statistics for domestic coal and natural gas production in non-OECD countries

	1974-1984	1984-1994	1994-2004	2004-2014
df	21	22	21	21
r	- 0,04	0,40	0,10	0,17
R^2	0,00	0,16	0,01	0,03
Reject H_0 if |r|	≥ 0,352	≥ 0,344	≥ 0,352	≥ 0,352
H_0 is	failed to reject	failed to reject	failed to reject	failed to reject

5.3.3 Prevalence of underground mining to decrease domestic coal production

To test the hypothesis whether the prevalence of underground mining could serve as a reason to decrease domestic coal mining, the thesis considered the following variables. The percentage of brown coal mined (n) was used as a proxy variable for the prevalence of underground mining, as 1-n provides the amount of coal mined in underground mines. Brown coal is usually mined in open-pit mines, whereas black coal is mostly produced in deep shaft mines. The logic behind the hypothesis is that those countries that are mostly endowed with deep lying coal resources and hence practice deep-shaft mining reduce coal production as this practice is less cost efficient. In such a scenario, the percentage of brown coal production in the overall domestic production is likely to be low. Therefore, the thesis correlated the share of brown coal production in the middle of the respective decade with change in domestic coal mining relative to the TPES of the country in the base year.

In order for the hypotheses to be tested, first of all the dataset was cleaned of those time periods where a country did not produce any coal at all. Contrary to some previous datasets, the explanatory variables in the brown coal dataset were not cleaned of those time periods where brown coal production did not take place at all, as the thesis is arguing that a country that is producing any amount of coal is also likely to be endowed with the generally more abundant brown coal grade resources. It is important to mention that in this analysis China has been removed from the dataset, as the country is reported to have a 100% share of black coal in production, however, in practice this is unlikely to be the case.

The null hypothesis (H_0) for all interval periods is that there is not a relationship between the share of brown coal in overall domestic coal production and changes in domestic coal mining relative to TPES, therefore H_0 is that $r = 0$. The alternative hypothesis (H_1) is that there is a significant negative correlation between the shares of brown coal production and the changes in coal mining relative to TPES, therefore H_1 is that $r \leq 0$. The level of significance, as discussed in the methodology is chosen to be 95%, therefore α=0,05. The degrees of freedom (df), and *r*-values for each decadal interval period are presented in the below table. Considering the number of objects in the dataset and the derived df-values, the alternative hypotheses should be rejected for each decadal interval, if *r* fails to be larger than 0,195-0,231, depending on the size of the dataset in each time period.

The results presented in Table 15 suggests that in none of the observed time periods there is a negative and significant relationship between the share of brown coal production and domestic coal production relative to TPES. The null hypotheses therefore cannot be rejected in in any of the time periods, hence suggesting that the share of brown coal in overall production does not seem to exert any influence on domestic coal mining. Although the negative relationship is observed in three of the four decades, but the level of the correlation is not significant in any of the cases.

Table 15: Correlation statistics for coal and brown coal mining worldwide

	1975-1984	1984-1994	1994-2004	2004-2014
df	49	50	63	59
r	-0,05	-0,08	0,09	-0,15
R^2	0,002	0,01	0,01	0,02
Reject H_0 if $\|r\|$	$\geq$ 0,231	$\geq$ 0,231	$\geq$ 0,195	$\geq$ 0,211
H_0 is	failed to reject	failed to reject	failed to reject	failed to reject

Further refining the dataset and dividing it into OECD and non-OECD countries did not provide any more significant results, hence the correlation statistics for this further analysis is not reported.

5.4 Correlations for decline of coal use in electricity generation

5.4.1 Decline in domestic coal mining to decrease coal usage in electricity generation

To test the hypothesis whether a decrease in domestic coal mining leads to a decrease in coal fired generation the thesis correlated changes in domestic coal production at the decadal level and relative to TPES in the base year with changes in coal fired electricity generation at the decadal level and relative to the total electricity production in the base year.

In order for the hypothesis to be tested, the thesis first applied some data cleaning for the list of 100 countries that produced the most electricity in absolute terms in 2014. Initially the dataset consisted of 400 data points, one for each decadal period for both coal production and usage in electricity generation. From this dataset, first those countries were removed, where coal was not at all mined and coal has not been used in the electricity generation mix. In order to avoid a zero-inflated dataset, in the second round of data cleaning the thesis removed those data pairs where either coal production or use in electricity generation represented 0%. By doing so, the number of data pairs were reduced from 400 to 215. Following these modifications to the dataset, the remaining countries were also classified as OECD or non-OECD, depending on their membership status to the organisation in 2017. With this differentiation in mind, there remained 111 OECD data points and 104 non-OECD data points within the dataset.

The null hypothesis (H_0) for all interval periods is considered to be that there is no relationship between the changes in coal use in electricity generation and changes in domestic coal production, therefore H_0 is that $r = 0$. The alternative hypothesis (H_1) is that there is a significant positive correlation between changes in coal use in electricity generation and changes in domestic coal production in the same period, therefore H_1 is that $r \geq 0$. The level of significance, as discussed in the methodology is chosen to be 95%, therefore $\alpha = 0{,}05$. The degrees of freedom (df), and *r*-values for each decadal intervals period are presented in the below table. Considering the number of objects in the dataset and the derived df-values, the alternative hypotheses should be rejected for each decadal interval, if *r* fails to be larger than 0,211-0,317, depending on the decade.

The thesis finds that in the case of all decades the null hypothesis can be rejected and the alternative hypothesis can be accepted, as there is a significant and positive correlation between the change of coal use in electricity generation and domestic coal production (Table 16). This relationship is the strongest in 1974-1984 when considering all countries, about 43% of the variation in coal use in electricity generation may be explained by the changes in domestic coal mining. Although the relationship is significant in all cases, but in 1984-1994 and 2004-2014 the correlation becomes rather weak, as in these instances the two considered variables are almost 20% more different than they are similar.

Table 16: Statistics for production and use in electricity generation considering all countries

	1974-1984	1984-1994	1994-2004	2004-2014
df	46	48	58	55
r	0,657	0,498	0,627	0,470
R²	0,431	0,248	0,393	0,221
Reject H_0 if *r*	≥ 0,317	≥ 0,231	≥ 0,211	≥ 0,211
H_0 is	rejected	rejected	rejected	rejected

To test further for this relationship, the thesis considered the already observed countries in two categories: OECD and non-OECD countries as of 2017. The below table shows the results for OECD countries (Table 17), for which the null and alternative hypotheses were the same as when considering all countries. Overall, it appears that the relationship between coal use in electricity generation and domestic coal mining appears to be slightly less strong in OECD countries than if considering all countries as well. Although in 1974-1984 and 1994-2004 the strength of the relationship is identical, in 1984-2004 the relationship breaks down in OECD countries as it is below the previously discussed case, but even more importantly, in 2004-2014 the thesis has failed to reject the null hypotheses, there is insufficient evidence that the correlation between coal use in electricity generation and domestic coal production is different from being zero.

Table 17: Statistics for coal use in electricity generation and domestic coal mining in OECD countries

	1974-1984	1984-1994	1994-2004	2004-2014
df	25	26	27	25
r	0,614	0,434	0,627	0,107
R²	0,377	0,188	0,393	0,012
Reject H_0 if $\lvert r \rvert$	≥ 0,323	≥ 0,317	≥ 0,311	≥ 0,323
H_0 is	rejected	rejected	rejected	failed to reject

From the above presented results, one can already deduce that there is a stronger positive relationship between changes in coal use in electricity generation and changes in domestic coal production in non-OECD countries than OECD countries. In this case, the null hypotheses can be rejected in all cases in favour of the alternative hypotheses (Table 18), therefore there is a significant and positive relationship between the two variables in non-OECD countries as well. The relationship is strongest in 1974-1984, where exactly half of the variation in coal use in electricity generation correlates to changes in domestic coal production, but even in the second period with the strongest correlation this figure is 47%. In 1984-1994 and 2004-2014, although the results being positive and significant, there is a lower degree of correlation in these time periods, however, the R^2-values indicate that in this subset of the data, the explanatory power of the domestic coal production is greater than when all countries were considered.

Table 18: Statistics for coal use in electricity generation and domestic coal mining in non-OECD countries

	1974-1984	1984-1994	1994-2004	2004-2014
df	19	20	29	28
r	0,707	0,528	0,688	0,531
R^2	0,500	0,278	0,474	0,282
Reject H_0 if |r|	≥ 0,369	≥ 0,36	≥ 0,301	≥ 0,306
H_0 is	rejected	rejected	rejected	rejected

5.4.2 Availability of nuclear power to decrease coal usage in electricity generation

To test the hypothesis whether an increase in nuclear electricity generation is associated with lower levels of coal fired generation the thesis correlated changes in nuclear power output at the decadal level and relative to total electricity supply (TES) in the base year with changes in coal fired electricity generation at the decadal level and relative to TES. Due to the unavailability of data though as compared to other correlations previously analysed, in this instance the first time period encompassed only 9 years from 1976-1984, with the base year being 1975 as opposed to 1974.

In this analysis as well, the thesis undertook some data cleaning before turning to the correlations; those countries and data pairs were deleted where coal was not at all used in the power generation mix. On the contrary though, those data pairs were not removed where nuclear power generation was not taking place at all, thereby observing those countries as well that increased or decreased coal usage yet did not develop nuclear power generation capacity. Following these modifications there remained 262 data pairs in the dataset.

The null hypothesis (H_0) for all interval periods is considered to be that there is no relationship between the changes in coal use in electricity generation and nuclear power generation, therefore H_0 is that $r = 0$. The alternative hypothesis (H_1) is that there is a significant negative correlation between changes in coal use in electricity generation and changes in nuclear power output in the same period, therefore H_1 is that $r \leq 0$. The level of significance, as discussed in the methodology is chosen to be 95%, therefore $\alpha = 0{,}05$. The degrees of freedom (df), and r-values for each decadal intervals period are presented in the below table. Considering the number of objects in the dataset and the derived df-values, the alternative hypotheses should be rejected for each decadal interval, if r fails to be larger than 0,195-0,231, depending on the number of observations in each time period.

Based on the results presented in Table 19 the thesis established that there is no significant negative relationship between coal and nuclear power generation. The r-values not only point to a positive relationship in two instances (1994-2004 and 2004-2014), but the relationship is also insignificant to a large extent, the R^2-values are indicating that at best the two sets of variables are only 1% the same and hence 99% different to each other. In light of this, in all cases the null hypotheses are failed to be rejected, hence there is not a significant and negative correlation between coal and nuclear fired electricity generation.

Table 19: Correlation statistics for coal fired and nuclear power generation

	1975-1984	1984-1994	1994-2004	2004-2014
df	50	53	64	65
r	- 0,01	- 0,02	0,07	0,09
R^2	0,00004	0,0003	0,005	0,01
Reject H_0 if $\lvert r \rvert$	≥ 0,231	≥ 0,211	≥ 0,195	≥ 0,195
H_0 is	failed to reject	failed to reject	failed to reject	failed to reject

To further investigate a potential relationship, the analysis has been narrowed down to focus on those countries that had nuclear power generating capacities in the time periods that are under consideration. This act however, narrowed down the dataset to a handful of countries, therefore a significant negative relationship could not be unrevealed even in these cases. Following this, the analysis made a distinction between OECD and non-OECD countries as well, but yet again, the null hypotheses were failed to be rejected in all cases, indicating that the rise of nuclear power is truly not associated with a decrease of coal fired generation. As these investigations did not leave to any significant conclusions, the detailed results are not presented.

5.4.3 Availability of other fossil fuels in the generation portfolio to decrease coal usage in electricity generation

To test the hypothesis whether an increase in the share of other fossil fuels in the generation portfolio is associated with a decrease in coal fired generation the thesis correlated changes in other fossil (oil and gas) power output at the decadal level and relative to TES in the base year with changes in coal fired electricity generation at the decadal level and relative to TES. As in the previous chapter, due to the unavailability of data as compared to other correlations previously analysed, in this instance the first time period encompassed only 9 years from 1976-1984, with the base year being 1975 as opposed to 1974.

The analysis again began with data cleaning, those data pairs were removed, where coal was not at all used in any of the time intervals. Similarly to the case of coal and gas imports though, the explanatory dataset did not provide a rational for further data cleaning, as all countries that used at least some coal in their electricity generation also used gas and oil in the national generation portfolio. Following the data cleaning, there remained 261 data pairs in the dataset.

The null hypothesis (H_0) for all interval periods is considered to be that there is not a relationship between the changes in coal use in electricity generation and other fossil power generation, therefore H_0 is that $r = 0$. The alternative hypothesis (H_1) is that there is a significant negative correlation between changes in coal use in electricity generation and changes in other fossil electricity generation in the same period, therefore H_1 is that $r \leq 0$. The level of significance, as discussed in the methodology is chosen to be 95%, therefore $\alpha = 0{,}05$. The degrees of freedom (df), and *r*-values for each decadal intervals periods are presented in the below table. Considering the number of objects in the dataset and the derived df-values, the alternative hypotheses should be rejected for each decadal interval, if *r* fails to be larger than 0,195-0,231, depending on the number of observations in each time period.

Table 20 shows that there is not a conclusive evidence for the correlation of the two variables in all time periods. In 1975-1984 there is a significant negative correlation, hence the null hypothesis can be rejected in favour of the alternative. In 1984-1994 the correlation is also significant, however, it is opposite of the expected sign, hence the null hypothesis is failed to reject in this time period, as an increase in other fossil fuels also brought about an increase of coal fired generation in the national electricity portfolios. In the last two time periods the *r*-values indicate a low level of correlation between the two variables, hence the null hypotheses cannot be rejected, there is not an inverse relationship between other fossil and coal fired generation in the electricity portfolios.

Table 20: Correlation statistics for coal and other fossil fuels in the electricity generation mix

	1975-1984	1984-1994	1994-2004	2004-2014
df	49	52	64	66
r	- 0,33	0,23	0,04	0,12
R^2	0,11	0,05	0,00	0,02
Reject H_0 if |*r*|	≥ 0,231	≥ 0,211	≥ 0,195	≥ 0,195
H_0 is	rejected	failed to reject	failed to reject	failed to reject

In order to further disentangle the potentially distorting effects of countries of different income levels, the analysis also looked at the differentiation between OECD and non-OECD countries with the same H_0 and H_1 hypotheses as before, also keeping the alpha level constant. The level of significance for OECD countries is different to all countries in that the null hypothesis was failed to be rejected even in 1975-1984, therefore in all time intervals in OECD countries there was not a significant negative correlation between coal and other fossil fuel use in the electricity mix (Table 21). Despite this, it is perhaps notable that the R^2-values were above those of in the case of all countries, though still insignificant.

Table 21: Correlation statistics for coal and other fossil fuel electricity generation in OECD countries

	1975-1984	1984-1994	1994-2004	2004-2014
df	28	28	30	29
r	- 0,27	0,34	0,13	0,24
R^2	0,07	0,12	0,02	0,06
Reject H_0 if $\|r\|$	≥ 0,306	≥ 0,306	≥ 0,296	≥ 0,301
H_0 is	failed to reject	failed to reject	failed to reject	failed to reject

The case is somewhat similar in the case of non-OECD countries as well, where in three of the four time intervals the null hypotheses were failed to be rejected, indicating that there is not a significant negative relationship between coal and other fossil fuel fired electricity generation (Table 22). Only in 1975-1984 could the significant inverse relationship be identified and hence the null hypothesis be rejected.

Table 22: Correlation statistics for coal and other fossil fuel based power generation in non-OECD countries

	1975-1984	1984-1994	1994-2004	2004-2014
df	19	22	32	35
r	- 0,44	0,19	0,05	0,07
R^2	0,20	0,04	0,003	0,004
Reject H_0 if $\|r\|$	≥ 0,369	≥ 0,344	≥ 0,275	≥ 0,275
H_0 is	rejected	failed to reject	failed to reject	failed to reject

5.5 Summary of findings based on correlations of non-coded variables

Table 23 shows the summary of the findings. Of the three tested hypotheses for a decline in domestic coal production, only increasing coal and natural gas imports showed a significant relationship, across three of the four time intervals. It appears that an increase in domestic natural gas production is rarely associated with a decline in domestic coal mining, and similarly, the share of domestic brown coal production does not seem to relate to any significant relationship with changes in domestic coal mining.

The case is highly similar to the reasons for a decline in coal use in electricity generation. It is clear that in all time periods, a decline in domestic coal production was associated with a decrease in coal fired generation as well, providing consistent values across the observed time periods. Contrary to expectations, there is not a significant evidence that an increase in nuclear power generation in a country is associated with a decline in coal fired generation. Furthermore, the availability of other fossil fuels within the electricity generation portfolio is rarely associated with a decline in coal use for power generation, only in the period of 1974-1984.

Table 23: Summary of the findings, with 'yes' and 'no' indicating whether the null hypotheses can be rejected

	Correlations	1974-1984	1984-1994	1994-2004	2004-2014
Correlates of decrease in coal production	Increasing coal and natural gas imports	no	yes	yes	yes
	Increase in domestic natural gas production	no	no	no	no
	Prevalence of underground mining	no	no	no	no
Correlates of decrease in coal use in electricity generation	Decline in domestic production of coal	yes	yes	yes	yes
	Availability of nuclear power in electricity mix	no	no	no	no
	Availability of other fossil fuels in electricity mix	yes	no	no	no

5.6 Correlations for decreases in domestic coal production and coal use in electricity generation using coded variables

In the previous sections it was found that it is only increasing coal and natural gas imports that exhibit a significant correlation with a decrease in domestic coal mining and in turn, it is only the decline in domestic production of coal that significantly correlates with a decrease in coal use in electricity generation. However, the results of the previous sections are largely influenced by relationships that are observed through growth instead of decreases, and could have been also influenced by rather high levels of growth, as for instance coal production grew in Brazil by 248% in 1975-1984 (Table 5). In order to account for this, the thesis took the two sets of variables that showed consistent significant correlations as exhibited in Table 23 and coded them to create two datasets of binary variables. In case of the dependent variables (coal production change over the decade relative to TPES and coal fired power generation relative to TES) a decrease was coded to the integer 1, while an increase was coded to the integer 0. Similarly, in the case of the independent variables (increasing coal and natural gas imports and decline in domestic coal production), a decrease was marked as 1, and an increase as 0. With these data manipulations, the order of magnitudes of the changes in the variables cannot influence the strength of the correlation, thereby the results of this analysis allows us to draw conclusions to what extent natural gas and coal imports represent a change in the decrease of domestic coal production and domestic coal production a change in coal use in electricity generation.

5.6.1 *Binary covariance of domestic coal production and natural gas and coal imports*

The interpretation of the results is similar to previous cases. The null hypotheses are that there is no significant relationship between the decrease in domestic coal production and therefore $r = 0$. The alternative hypothesis is that there is significant negative relationship between domestic coal production and natural gas and coal imports, hence H_1 is that $r \leq 0$. The alpha level was kept at 0,05, so the significance level of these analyses is the same as before.

Table 24 shows that when the magnitude of the change in domestic coal and associated natural gas and coal imports is not considered, the explanatory power of the covariance breaks down significantly, it is only in 1984-1994 when the null hypothesis can be rejected. Although the expected negative relationship is observed in three of the four cases, but two of these correlations prove to be insignificant. Therefore, a change in natural gas and coal imports is rarely associated with a significant change in domestic coal production. Even if it does, as it does in 1984-1994, the strength of the correlation is relatively weak, as the R^2-value suggests the two datasets are only 5% similar, but in fact 95% different from each other.

Table 24: Correlation statistic for coded coal production and natural gas and coal imports worldwide

	1974-1984	1984-1994	1994-2004	2004-2014
df	50	51	64	61
r	- 0,17	- 0,23	- 0,15	0,12
R^2	0,03	0,05	0,02	0,01
Reject H_0 if |r|	≥ 0,231	≥ 0,211	≥ 0,195	≥ 0,195
H_0 is	failed to reject	rejected	failed to reject	failed to reject

5.6.2 *Binary covariance of coal fired electricity generation and coal production*

The level of covariance is much greater and indeed significant in the case of coal fired electricity generation and domestic coal production. The null hypotheses for all time periods were that there is not a significant relationship in the changes in coal fired electricity generation and domestic coal production, therefore H_0 is that $r = 0$. The alternative hypotheses are that there is a significant positive relationship between the two variables, therefore a decrease in domestic coal production is also associated with a decrease in coal fired electricity generation, hence H_1 is that $r \geq 0$. The alpha level again was set at 0,05.

Table 25 shows that the null hypotheses can be rejected in all instances, and indeed there is a significant positive relationship between coal use in electricity generation and domestic coal production. Despite the relationship being significant and the fact that the null hypotheses can be rejected in favour of the alternative in all analysed time periods, the strength of the correlation is not particularly large, at maximum are the two datasets 19% similar, which still leaves room for an 81% difference between the two variables.

Table 25: Correlation statistics for coded coal in electricity generation and domestic coal production worldwide

	1974-1984	1984-1994	1994-2004	2004-2014
df	46	48	58	55
r	0,302	0,373	0,226	0,440
R^2	0,091	0,139	0,051	0,194
Reject H_0 if $\|r\|$	≥ 0,231	≥ 0,231	≥ 0,211	≥ 0,211
H_0 is	rejected	rejected	rejected	rejected

6 Discussion

As the literature on energy transitions showed it, countries often take different routes to ultimately arrive to the same or highly similar energy mixes. For instance in the 19^{th} century, although Germany did not lack firewood resources, yet it transitioned to a coal based economy, an outcome that happened in the United Kingdom centuries before but at least partially because of the shortages of woody biomass. These historical transitions exemplify the diversity through which energy transitions may materialise, and which are also exhibited in the results of the thesis.

First of all, the thesis identified 15 countries that reduced coal production significantly in at least one non-consecutive decade in 1975-2014, 7 of which are non-OECD countries. As the majority of the decreases happened in the latest time period, it would be incorrect to conclude that these were only one-off events, but in 5 of the 7 non-OECD countries that experienced a decline in 1975-2004, the declining period was always followed by an increasing period. In terms of significant and persistent decreases, the thesis identified 11 such countries, 10 of which are OECD nations, with the exception of Romania. In electricity production, there are 16 countries that significantly decreased coal usage, 12 of which are again OECD countries, 10 of which form a well identifiable corridor in Central Europe. The number of countries that both significantly and persistently reduced coal usage in electricity generation is less numerous, only 4 OECD countries managed to do that. Overall, OECD countries dominate these two sets of nations and non-OECD countries often experienced a rebound in either coal production or usage post a decade that exhibited a decline.

Overall, the hypotheses set up by the thesis cannot be considered entirely successful in finding out the correlations of coal production and usage, as only two of the six hypotheses provide the expected outcome and significance.

First, the thesis found that there is a significant negative relationship between domestic coal production and coal and natural gas imports in three of the four observed decades, and this relationship is stronger in OECD countries than in non-OECD countries. The explanation behind the covariance is rather simple: coal and especially coal in the historical past that is the focus of the thesis, is basically irreplaceable in many of its applications, whether that is electricity generation or industrial application. Therefore, if coal production in a country becomes uneconomic or impossible, it is likely that the country will import the quantities of coal needed for its applications. This is rather bad news for the global climate. The thesis has shown that global coal production is at present growing at least twice as fast as global coal imports, but even if production growth slows down, countries are likely to then simply import the commodity or natural gas to be used domestically. The fact that this relationship is stronger in OECD countries than non-OECD countries is perhaps not as surprising either, as OECD countries can perhaps better afford to import the commodities. Also, OECD countries may have the resources to support a closing coal industry, as it happened in the case of France and the Netherlands as well, where coal miners enjoy special benefits, premature pensions and other subsidies provided by the government in exchange of the closure of the mines. It is also important though to reflect on how this relationship changed when both the independent and dependent variables were coded into binary variables. In this case, the relationship broke down, and there was only one decade in which the significant negative relationship could be observed. This suggests that when the magnitude of changes are disregarded in both variables, then domestic coal production is not as sensitive to changes in natural gas or coal imports. This is likely to be the case as when coal production grows, it does so as a result of economic growth, which usually translates into the increase of imports as well, pointing towards a positive correlation between coal mining and imports. However, when coal production declines it needs to be substituted by something, as total energy demand is unlikely to change. Increasing imports make up for this difference, hence the negative relationship, but as there are more pairs of data with increases rather than decreases, the relationship is expected to be less strong as well. Despite the thesis having a primarily past oriented focus, it is important to mention though that if global natural gas trade will intensify as a result of the significant investments and developments in the LNG sector, then the global uneven distribution of natural gas resources may pose a lesser obstacle for gas to replace coal at a large scale. It is also arguable though that if global gas trade will intensify and pricing becomes more competitive, then the volatility that characterise the global oil market could also surface in natural gas markets, which in turn can affect the extent to which natural gas imports could replace domestically mined coal.

Secondly, changes in domestic natural gas production do not seem to exhibit any meaningful covariance with changes in domestic coal production, the expected negative association could not be determined from the data. It is arguable that the reason for this is the different distribution of the resources globally, as coal is generally available in more countries than natural gas resources, hence countries develop both of these fossil sources of energy if endowed with them, instead of substituting them for each other, such as the case was in the Netherlands and the United Kingdom. Also, the development of the two resources require a rather different sort of knowledge, the companies that develop coal and gas deposits are generally differing companies, as coal is mainly targeted by traditional mining companies, while natural gas for a long time has been a side product of oil extraction. As a result, if a country already has an established coal mining sector, it is perhaps more difficult for the domestic sector to reorientate itself for the extraction of natural gas, thus the case of the Netherlands where the national coal company was given a share in the development of the domestic natural gas fields is rather the exception than the rule. It is also telling that in the case of non-OECD countries one of the time periods revealed a significant positive relationship, suggesting that industrialising countries are seizing the opportunity if they can to meet often rapidly rising energy demand.

Thirdly, the thesis did not find any significant relationship between domestic coal output and the share of brown coal in overall coal production, which is rather controversial, considering the experiences of France and especially the United Kingdom. It is arguable that if the share of brown coal is not associated with changes, nor negative nor positive with domestic coal production, then the economics of coal extraction does not seem to be a decisive factor in the amount of coal mined. As the thesis presented in the literature review, open-pit mining not only became more prevalent in the 20th century, but the mining in open pit mines is generally more cost efficient, therefore it is surprising that the share of brown coal does not seem to covary with domestic coal production. The thesis proposes that national coal industries are usually supported by various subsidies, such as in the experience of the United Kingdom before or Germany, which could have the capacity to mask the inefficiencies of a domestic coal mining sector that is perhaps producing more black coal in generally less cost efficient underground mines.

Turning to the correlations of coal use in electricity generation, the thesis found that the change in domestic coal production is indeed positively associated with coal use in electricity generation, even if this positive relationship has likely to have been established through growth rather than declines. It is found that in all considered time periods, there is a rather strong positive relationship between the two variables. If the positive relationship though is established through growth, then one would also expect that if coal production cannot expand further, then imports should take over to supply the domestic coal fired power plant fleet. As presented before though, there is a negative relationship between domestic coal production and coal and gas imports, however, this relationship is not as strong as the one between coal use in electricity generation and domestic coal production, therefore it is arguable that domestic coal production is unlikely to be perfectly compensated by coal imports, if necessary. The observed covariance is somewhat less strong in three of the four observed decades in the case of OECD countries, consequently stronger in non-OECD countries overall. This latter finding is also substantiated by the fact that it is those regions in the world that comprise of non-OECD countries that experience the fastest growth in both coal based electricity generation and domestic coal production. After coding the variables, it is reassuring that the relationship remained both positive and significant in all four decades, even though the strength of the association decreased to below 20% in all cases. Overall therefore, the thesis argues that a decrease in domestic coal production is a necessary condition for coal usage to decline in electricity generation, as imported fossil fuels only imperfectly substitute domestic production. Again, this is rather bad news for the global climate, as coal reserves are vast in many rapidly industrialising non-OECD countries, where the association showed an even greater strength. Based on the unburnable carbon concept introduced by Meinshausen *et al.* (2009), these resources will need to stay in the ground, which is an immense challenge for international environmental and economic policy. This challenge will be even more immense considering that coal production is growing four times faster globally than coal imports, therefore the decarbonisation of the electricity industry will prove to be even more difficult.

The thesis did not find a significant relationship between coal use in electricity generation and nuclear power output. Despite nuclear having the potential to provide for reliable base load generation, in practice it is unsupported that the technology fulfils such a role. The thesis proposes that there are multiple reasons why this might be the case. First of all, France itself developed its nuclear power capacity with energy security considerations heavily in mind. There are though only a few number of countries that have the capacity to not only build but to operate in the long run a nuclear power plant, therefore countries that consider energy security and security of supply as of primary importance will unlikely to trade their coal based power generation capacities to nuclear generation. Second of all, as the case of France exemplifies it, nuclear was built to meet primarily increasing energy demand, nuclear power thus rather complemented coal based production, rather than replaced it. It is also telling that there is not a difference between OECD and non-OECD countries. While arguably non-OECD countries lack the resources and experience to manage nuclear power within an electricity system, nuclear power does not seem to correlate in any way in OECD countries either, many of which are nuclear power operators.

Finally, the availability of oil and natural gas in the generation portfolio shows a weak but significant negative relationship in the first decade, but provides no evidence for the rest of the time periods. This relationship though is only recorded in the case of non-OECD countries, and not OECD countries. Despite this single significant time period, the thesis argues that it is likely to have been recorded because of the oil crises in the 1970s. As the prices of oil and then linked natural gas increased both in 1973 and 1978, countries shifted away from these resources, in fact oil based electricity production was basically ceased, only remaining significant in major oil producing countries, creating the basis for increases in coal based generation, hence the negative relationship observed in the first period. This substituting effect could have been more significant in non-OECD countries, perhaps as a result of them being more exposed to international price fluctuations and their economic effects. The fact that oil and natural gas in the generation portfolio does not seem to exhibit covariance with coal based generation discredits the experience of the United Kingdom and the Netherlands as well, as both of these countries decreased coal use to the advantage of natural gas. It is also telling though that despite natural gas being a more versatile commodity than coal and therefore has more usage alternatives, but coal production also did not exhibit covariance with natural gas production, therefore it is perhaps not as unusual that in electricity generation the two fuels are not substitutes of each other at the systems level either.

While the thesis used a historical approach and a rather narrowed down set of hypotheses to identify correlations between coal mining, usage and potential alternatives, it is not to suggest that other factors could not play a decisive role in reducing either coal production and usage in electricity generation. Considering the historical take on the issues, the observed sets of variables are justified, however, in more recent times other variables could perhaps yield other, even more noteworthy results. For example, although renewable electricity replacing coal fired generation is not rooted in the historical energy transitions discourse, it is perhaps of even greater significance for future energy transitions to come by. While Han *et al.* (2016) identify renewable energy as an important factor for peak coal to happen in China, other authors such as Wang *et al.* (2013) go further by stipulating that renewable energies will have a larger influence in replacing coal than oil and gas. While this argument does not seem to hold true in the context of historical energy transitions, however, future research could also target this hypothesis. Further research should also concentrate on establishing causality between the here observed and significant sets of variables, so that not only the coexistence of the variables can be identified, but the path that leads to the declined use and mining of coal can be traced.

7 Conclusions

The purpose of this thesis was to first of all identify countries that managed to significantly and persistently reduce coal mining and coal usage in electricity generation and secondly, identify common characteristics that covary with changes in coal output and use in electricity generation, thereby identifying those factors that can lead to lower levels of coal mining and use in power generation, which in turn could lead to lower levels of carbon emissions from the fossil fuel that is responsible for the largest share of global carbon emissions.

Through the literature review, the thesis identified and introduced in detail three case studies, namely of the United Kingdom, Netherlands and France, as these countries managed to significantly decrease coal production and the commodity is less used in their electricity generation portfolio. Based on the experiences of these countries, the thesis argued that the changes in natural gas and coal imports, domestic natural gas production, and the share of brown coal in the overall production could significantly correlate with changes in mining output in other countries as well, while in electricity generation, the thesis tested hypotheses for changes in domestic coal production, share of nuclear power generation and share of other fossil generation within the total national electricity supply.

In answering the objectives of the thesis, the thesis formed hypotheses deductively based on the arguments found in the literature, which were then tested using the Pearson product-moment correlation coefficient. In setting up the variables to be tested, the thesis most often measured changes in relation to the total primary energy supply or the total electricity supply in the countries, therefore the results are comparable to each other.

In first of all providing a global overview of the coal sector, the thesis demonstrated that coal production is increasing four times faster than coal trade, and even without the two largest coal producing regions considered, the rate of change remains twice as fast in coal mining which points to the fact that not only the two biggest coal producing nations (USA, China) are increasing their output, but other smaller producers as well, who so far did not account for such a large share of the overall global coal output. From a transition management perspective, this increases the number of actors that are required for a shift in the global energy mix, and may also suggest that technological advancements that have the capacity to make coal usage more sustainable in the long term will also have a role to play.

From a global environmental perspective, the correlations identified in coal mining and use in electricity generation point to little case of optimism with regards to peaking emissions from coal.

The thesis found a significant negative relationship between domestic coal production and coal and natural gas imports, thus it appears that if due to whatever reason a country is unable to mine coal, they will replace the commodity with imported fossil fuels, thereby only displacing the environmental effects and pollution associated with mining. Changes in natural gas production or the share of brown coal in overall coal production do not show any relationship with changes in domestic coal mining, therefore the assumption that natural gas, as a cleaner resource will replace coal is unfounded. Also, lower grade and therefore more polluting brown coal production does not influence coal output, potentially pointing towards the fact that national coal industries are often subsidised to the extent that the economics of mining changes and production levels are kept up despite high shares of generally less cost efficient black coal mining practices. These factors point towards the fact that in the past as long as a country had coal resources, those have been tapped and developed, and if necessary replaced by import sources.

The results are similar with regards to coal based power generation. Changes in coal based generation only show a significant and positive correlation with changes in domestic coal production, therefore an increased coal based electricity output is usually met from increases in domestic mining, and in principle vice versa. Despite being practically free of carbon emissions, there is no evidence that the adoption of nuclear power changes coal based output at all, and also the availability of other fossil fuels in the generation portfolio only showed a significant negative association in 1975-1984, which is likely the result of the oil crises of the decade which likely have made many countries to trade off oil and gas based generation for coal based power production. Overall therefore, it appears that the key to decrease carbon emissions from coal based generation, it is imperative to focus on the mining practices and decisions of individual countries. But as it is mainly OECD countries that managed to reduce coal use in electricity production so far, it provides for little optimism as non-OECD countries have expanded most rapidly coal based generation in recent years.

The thesis tested six hypotheses to identify characteristics that commonly characterise coal industries, however, the research leaves indeed room for further development and refinement and thus its results should be interpreted as an early contribution to an emerging field of energy transitions. As the work only tested for correlations, it was unable to identify causations and most importantly directions of causality between the tested variables, which should arguably be the next step in finding the factors that previously lead to the declined use and mining of coal. The findings of the thesis could indeed be useful in providing a basis for such further research efforts.

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