

Calculating the water footprint of fossil fuel extraction and trade in Canada and the U.S.

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ABSTRACT

Due to drought conditions exacerbated by climate change, the amount of energy that countries can extract and trade may become limited. Although the water footprint of biofuel production has been highly studied, fossil fuel extraction has not been examined even though it is currently the most commonly used source of energy worldwide. I calculated how much water is needed for coal, oil, and natural gas extraction in Canada in the United States, as well as how much water is associated with the trade of energy in the two countries. The water footprint of oil is the highest of the three fossil fuels, and it has generally been increasing over time for both countries. While the production and water footprint of coal has been slightly decreasing over the years, the water footprint of natural gas has been rapidly increasing in recent times. Oil accounts for the majority of the water footprint of trade. While Canada and the U.S. are both major producers of oil, Canada is a net exporter of virtual water whereas the U.S. is a net importer. More transparent reporting will allow us to calculate more accurate water footprints and analyze water consumption of other major global producers of energy besides Canada and the U.S.

KEYWORDS

Coal, oil, natural gas, virtual water trade, water energy nexus

INTRODUCTION

A water footprint is defined as the amount of freshwater used in the production or supply of a good, such as energy (Hoekstra and Mekonnen 2012). Calculating and examining this value is important because energy extraction requires large water inputs, but the countries that produce the most energy globally are located in the most arid regions of the world and are the most affected by water scarcity (Mielke et al. 2010). For example, California is a major producer of energy in the United States, and they allocate 49% of freshwater withdrawals for thermoelectric power (Wilson et al. 2016). However, major cities that produce energy in the state are located in arid regions, which causes citizens to lose energy during periods of drought because power plants require water to operate (Gober 2010). Therefore, while agricultural irrigation currently uses seventy percent of the global water supply, countries will need to allocate more freshwater to urban areas as the demand for energy increases as a result of rapid urbanization and population growth (Shevah 2015).

In order for countries to manage their water and energy supply so that they can allocate resources as necessary, they must first calculate how much water they are consuming to extract fossil fuels. Coal mining operations are highly water-intensive as they use water to mine and wash the coal (Grubert et al. 2012). The coal is then transported from the processing plant to the end destination via slurry pipelines, which also requires water. Oil has three recovery methods- primary, secondary, and tertiary. Primary is the oldest recovery method and is used to extract conventional oil that is near the earth's surface (Rosa 2016). However, countries have depleted most of these reserves and have to rely on in situ drilling methods (secondary and tertiary recovery) to drill deeper into the earth (Farrell and Brandt 2006). Secondary recovery involves water flooding and tertiary recovery methods, such as hydraulic fracturing and horizontal drilling, require additional inputs of energy and chemicals (Rosa 2016). There are various different tertiary methods, such as air injection and CO₂ injection, that all require different amounts of water. However, primary recovery is the least water intensive while tertiary recovery methods generally require the most water. However, oil is mostly transported through pipelines but do not require water to facilitate movement like coal and natural gas do. Conventional natural gas has a negligible water footprint, but countries such as Canada and the U.S. use hydraulic fracturing and horizontal drilling to extract shale and tight gas that is found in shale formations and sandstones deep under the earth's surface (Rosa 2016). All natural gas requires water to transport through slurry pipelines (Mohitpour et al.

2007).

However, not all regions in the world have enough water or energy resources to adequately supply for their population and therefore rely on the trade of energy to meet their demand. For example, only 59% of biodiesel's water footprint in the OECD and EU27 countries were internal and the rest was imported from other countries (Rulli et al. 2016). In the United States, 27% of non-agricultural water use is consumed by energy, but this percentage may decrease due to drought (Mielke et al. 2010). This decrease will result in energy shortages for not only local citizens, but also the countries that rely on U.S. exports. Given the rising dependence on global trade, countries must not only calculate the amount of water they are using to produce energy, but also how much water they are importing through the form of energy (Carr et al. 2013).

It is important to study fossil fuels because they are the most commonly used sources of energy worldwide (EIA 2017). In this study, I examined how much water is used to extract coal, oil, and natural gas in Canada and the U.S in my study. In order to do so, I quantified how much energy is being produced with each method of extraction and find out how much water each method uses. I also calculated how much water is being traded in the form of energy in both countries.

METHODS

Data Source Selection

To find out how much oil, coal, and natural gas was produced in the U.S. and Canada, I used data provided by the International Energy Agency (IEA) and an energy report conducted by BP (BP 2017, IEA 2017) (Figures A1-A3). I limited this study to these two countries because of the lack of global data. While these datasets only reported total production, I used the Oil Sands Magazine and the Oil & Gas Journal for more specific data of how much unconventional energy was produced, such as oil sands and shale gas. I examined temporal trends based on the available data, which was 1981-2015 for coal in the U.S. and Canada, 1968-2016 for oil in Canada and

1965-2015 in the U.S., and 1990 to 2015 for natural gas in the U.S. and Canada. I quantified oil in terms of thousand barrels daily, coal in million tons, natural gas in billion cubic meters, and water in million metric tons.

Assumptions

Water consumption by process/method

Coal. Coalbed methane uses a negligible amount of water so I reported it as using 0 gal/MMBtu of water, as well as for “other”, “lower 48 offshore” and “Alaska” (Mielke et al. 2010). I also assumed that all the coal produced in each country went through a mining, washing, and transportation process as reported in a previous study (Mielke et al. 2010) (Table A1).

Oil. For Canada, I assumed that anything that was not mined or drilled from oil sands was from primary and secondary recovery. This was because there was not enough data to determine whether other tertiary methods besides oil sand mining and drilling were used (Table A2). Because there was no data available to differentiate primary and secondary recovery, I reported them as lower and upper estimates, using water consumption values found in a previous study (Wu et al. 2009). For the U.S., I assumed that primary recovery was no longer used once secondary production began in 1966 (Berman 2016). This may not model the real situation because primary recovery was more gradually phased out, but it was found that primary recovery accounted for a negligible proportion of the water footprint (Mielke et al. 2010). I began to account for tertiary recovery in 1982, which was when these technologies were introduced and used in the U.S. (Berman 2016). Because the datasets did not specify the tertiary methods used for oil recovery, I assumed that air and CO₂ injection were used because they are the most commonly used methods of extraction (Alvarado and Manrique 2010). I reported the calculations as a lower estimate (air injection) and upper estimate (CO₂ injection) and assumed that 80% of total production was from secondary recovery and 20% was from tertiary recovery as found in a previous study (Mielke et al. 2010) (Table A3). I assumed that all oil shale in the U.S. was underground- or surface-mined because there are no water estimates for in-situ mining (Mielke et al. 2010).

Natural gas. For natural gas in both countries, I had to assume that water consumption came strictly from shale and tight gas extraction and pipeline transportation (Table A4). I assumed that tight gas consumed the same amount of water as shale gas even though they come from different formations. This was because previous studies only found water consumption values for shale gas (Mielke et al. 2010).

Water-energy trade

To analyze how much fossil fuel is traded, I calculated how much was imported or exported in each country. Using a previous study that calculated the total amount of fossil fuels produced and consumed between 1965 and 2016, I calculated the difference between the amount produced by the amount consumed in each country (BP 2017) (Figures B1-B3). A positive value indicated that the country was an exporter and a negative value indicated that the country was an importer of fossil fuels for that specific year. I then estimated how much water would be required to produce the amount of fuel that was traded by finding what percent each extraction method was used to produce the total amount of energy each year. For example, I had assumed that 80% of the oil produced in the U.S. in 1983 was from secondary recovery, so 80% of the oil traded in the U.S. in 1983 was from secondary recovery. I then used these values to calculate the total water footprints of the trade of coal, oil, and natural gas in both countries. Again, a positive value indicated that the country is a net exporter of virtual water whereas a negative value meant that it was a net importer.

Data Analysis

I compiled the data into an Excel sheet with time set as the independent variable and water footprint value set as the dependent variable. I then identified which fossil fuel was the most water intensive for each country. To visualize temporal trends, I graphed total energy production and water footprint against time. I noted if energy production and water consumption generally increased over time or if there were any fluctuations. I also showed which parts or methods of the extraction process were the most water intensive by breaking down the total water footprint into separate components. To show any trends of trade over time, I graphed the amount of energy and water imported (negative values) or exported (positive values) for each country.

RESULTS

Water Consumption by Process/Method

Coal

I found that the water footprint of coal extraction in Canada peaked in 1997 and then decreased by 22% by 2015 (Figure 1). The water footprint of coal peaked in 2008 in the U.S. and then decreased by 24% by 2015 (Figure 1). Transportation accounted for 62% of the total water footprint for coal extraction in 1981 both Canada and the U.S. and this proportion stayed the same in 2015 (Figure 2).

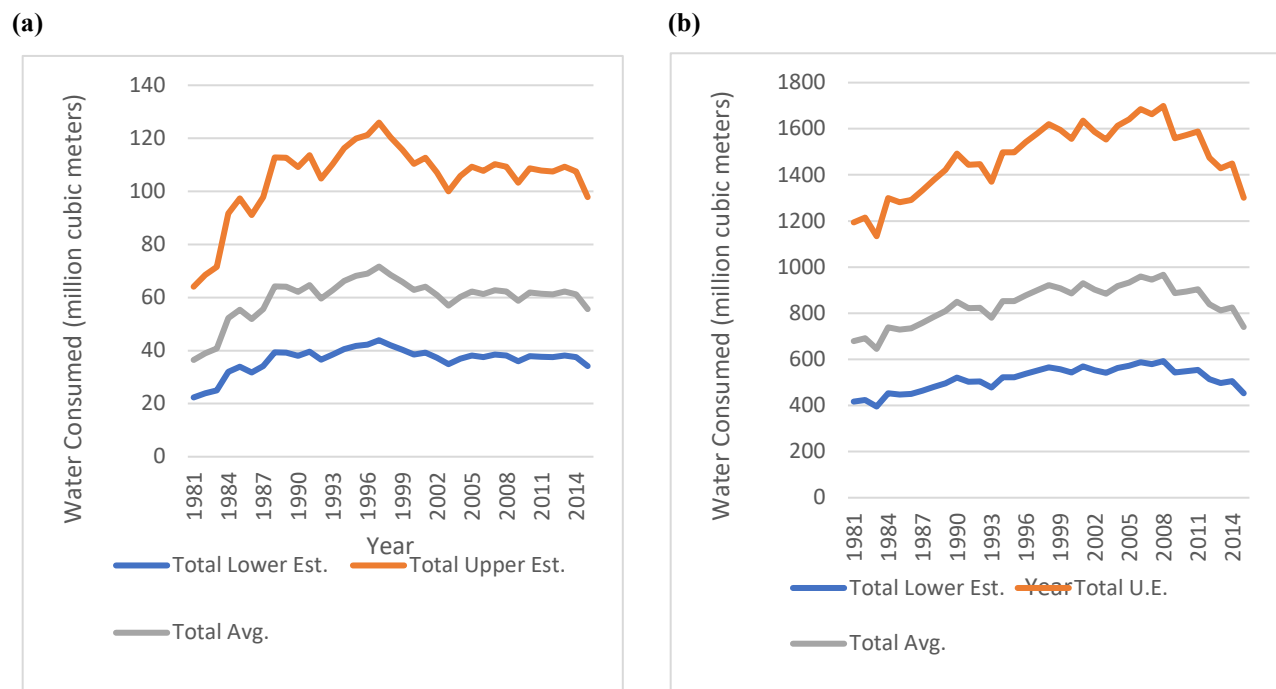


Figure 1. Water footprint of coal extraction. I calculated the lower, upper, and weighted average water footprints of (a) Canada and (b) U.S. based off of water consumption values calculated in Mielke et al. 2010's study.

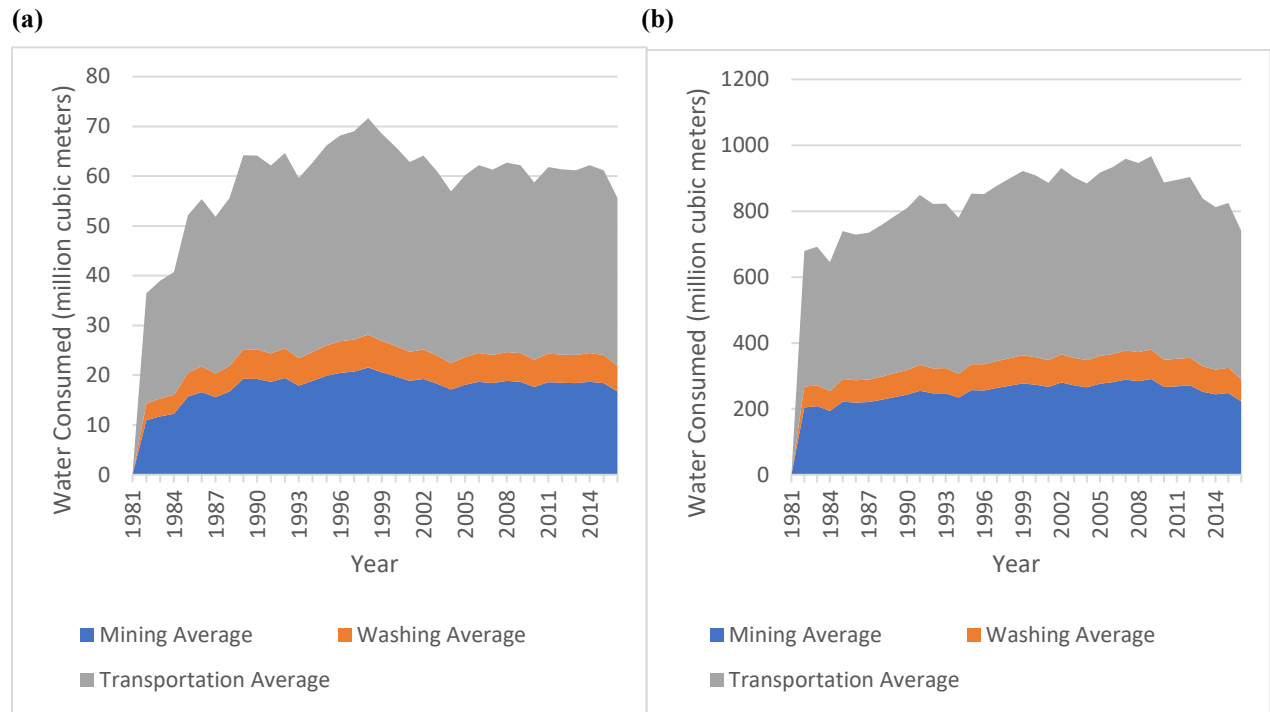


Figure 2: Average water consumption of coal by process. I broke the total water footprint of coal up by each process using the average values of mining, washing, and transportation for (a) Canada and (b) the U.S.

Oil

The water consumption of oil has generally increased in Canada over time, increasing by 2,844% from 1968 to 2016 (Figure 3). Water consumption of oil in the U.S. had increased by 4,605% from 1965 to 1966 when secondary recovery was introduced and primary recovery was completely phased out, but decreased by 21% from 1966 to 2006 (Figure 3). It then increased again by 108% from 2006 to 2015. Secondary recovery was the majority of the total water footprint of oil, accounting for almost 100% in Canada in 1968 and 100% in the U.S in 1966 (Figure 4). However, these percentages decreased to 50% in Canada by 2016 and 70% in the U.S. by 2015.

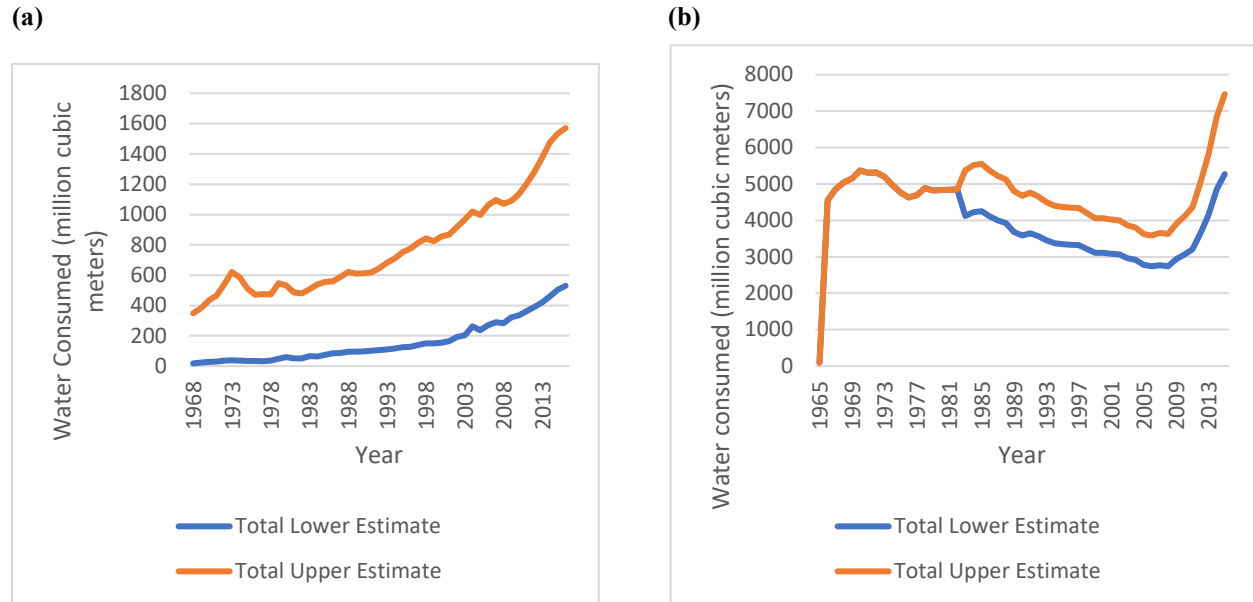


Figure 3. Water footprint of oil extraction. (a) Canada: The lower estimate is from primary, secondary, and surface mining recovery while the upper estimate was calculated using primary and secondary recovery as well as in situ drilling recovery. (b) U.S.: The lower estimate includes primary, secondary, and air injection values while the upper estimate includes primary, secondary, and CO₂ injection values.

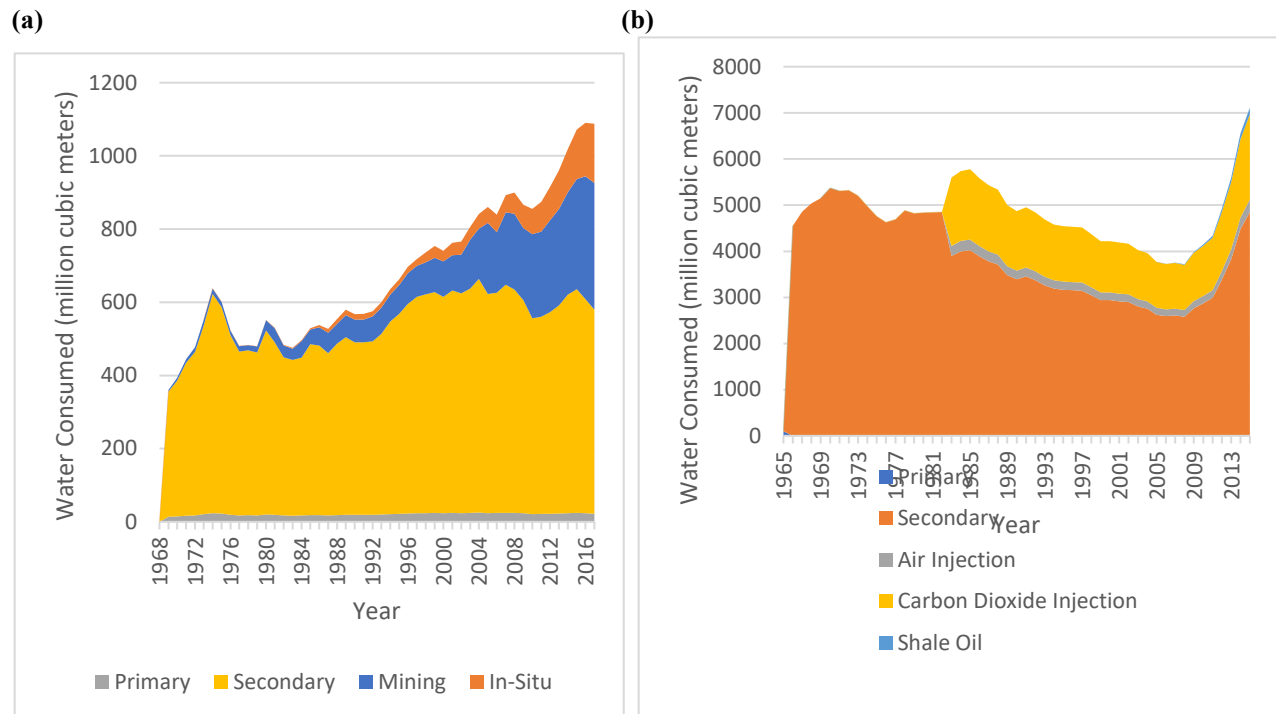


Figure 4. Water consumption of oil by method. I broke the total water footprint of oil up in (a) Canada: by primary and secondary recovery, mining (lower estimate), and in-situ drilling (upper estimate) and (b) the U.S.: by primary, secondary, air injection (lower estimate), and CO₂ injection (upper estimate).

Natural gas

Water consumption of natural gas in Canada appeared to have peaked in 2006, having increased by 15% since 2000 (Figure 5). Consumption then decreased by 10% until 2009, at which point it increased by 14% until 2014. In the U.S., the water consumption of natural gas has constantly increased from 1990 to 2015 (Figure 5). However, there is a sudden spike beginning in 2005. The magnitude of change from 1990 to 2005 was only 15%, while the magnitude of change from 2005 to 2015 was 89%. Transportation was also the major input of water for natural gas in both countries, accounting for almost 100% in Canada in 2000 and 79% in the U.S. in 1990 (Figure 6). However, these percentages again declined as the percentage of shale gas and tight gas increased, dropping transportation to 63% in Canada by 2014 and 54% in the U.S. by 2015.

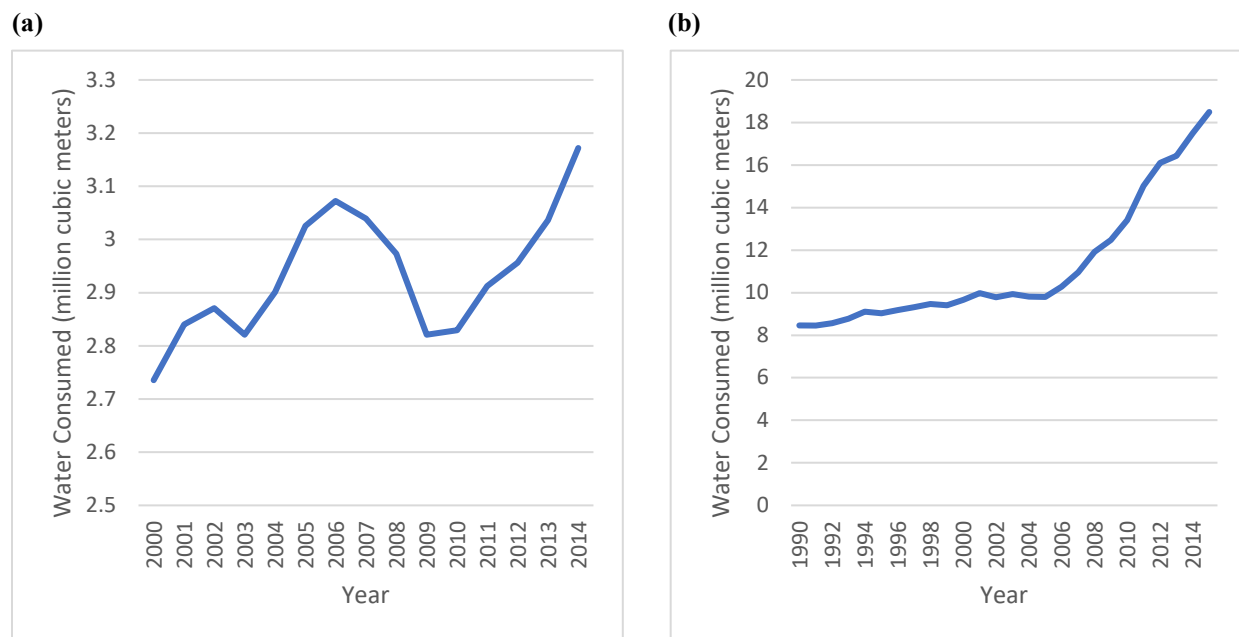


Figure 5. Water footprint of natural gas extraction. This is just the water footprint of shale and tight gas as any other gas was assumed to have a negligible water footprint in (a) Canada and (b) the U.S.

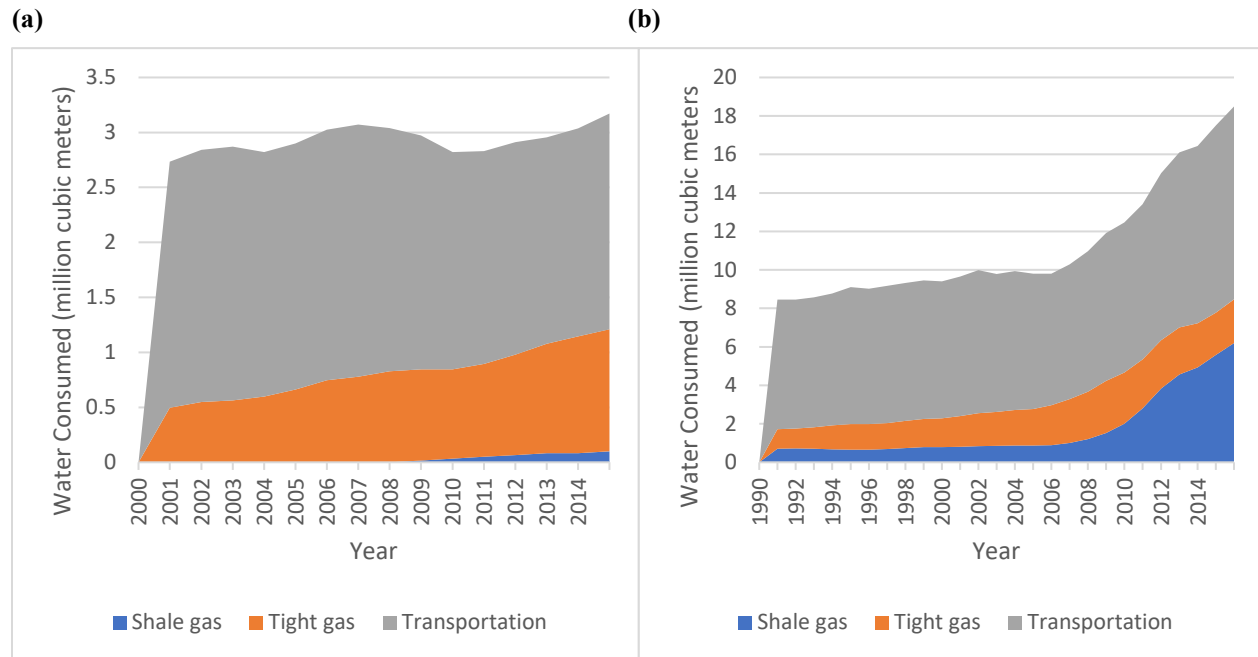


Figure 6. Water consumption of natural gas by process. I found how much water is consumed by shale gas, tight gas, and transportation of all natural gas in (a) Canada and (b) the U.S.

Water footprint of trade

I found that both Canada and the U.S. are generally exporters of coal from 1981 to 2016, but the amount they export has increased by 2,017% in Canada and decreased by 90% in the U.S. (Figure 7, Figures B1-B6). Canada is historically a net importer of oil since 1965 but has continually been an exporter since 1983 whereas the U.S. has constantly been an importer of oil since 1965 (Figure 7). The amount of oil Canada exports has increased by 1,380% from 1983 to 2016 while the amount of oil the U.S. imports has increased by 451% from 1965 to 2006 and decreased by 48% from 2006 to 2016. Lastly, Canada is a net exporter of natural gas while the U.S. is a net importer (Figure 7). While the magnitude of change was 31% from 1970 to 1989 in Canada and 33% in the U.S. from 1970 to 1986, trade rapidly increases by 281% from 1989 to 2002 in Canada and 2,700% from 1986 to 2002 in the U.S. There is then a rapid decrease by 44% in Canada and 94% in the U.S. until 2015. Oil has the largest water footprint of trade, accounting for almost 100% of Canada's exports and of U.S. imports (Figure 8).

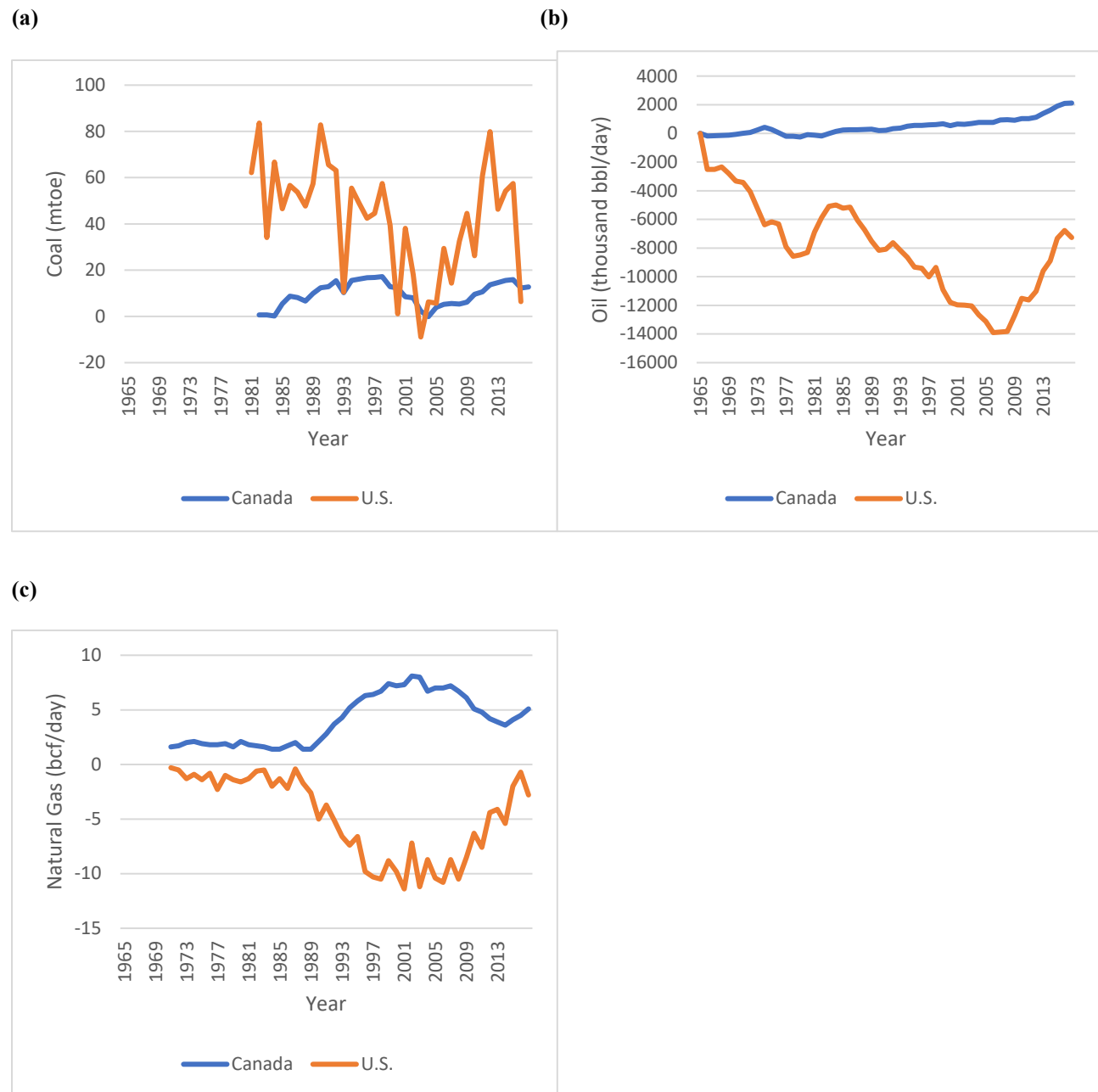


Figure 7. Net trade in Canada and U.S. I compared how much (a) coal, (b) oil, and (c) natural gas was imported to or exported from Canada or the U.S.

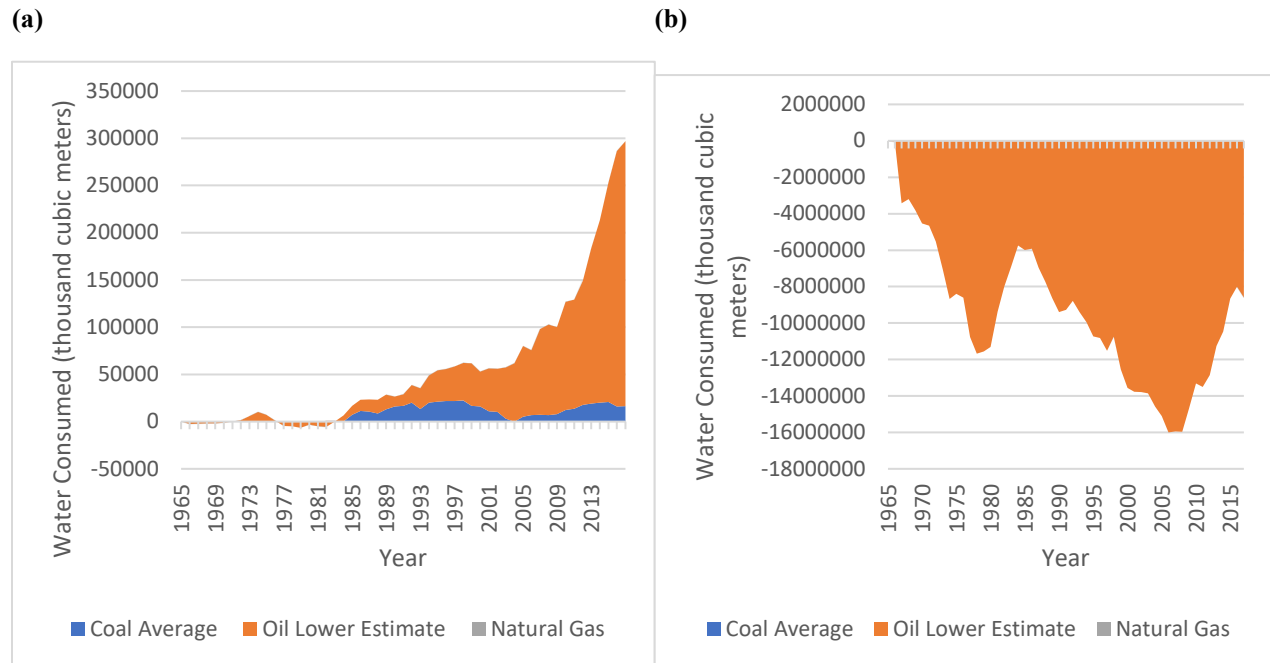


Figure 8. Trade of water associated with coal, oil, or natural gas extraction. I found how much water (a) Canada and (b) the U.S. are importing or exporting when it trades coal, oil, and natural gas. I used the average water consumption values for coal and the lower estimates for oil.

DISCUSSION

Both the U.S. and Canada have been using increasing amounts of water to extract fossil fuels as well as trading increasing amounts of fossil fuels. I found that there are higher water footprints in more recent years for oil and natural gas extraction in both countries. The trend in water consumption for coal extraction is harder to generalize because coal production continuously oscillates. We have also found that in modern times, the U.S. is generally a net exporter of coal but net importer of oil and natural gas whereas Canada is generally a net exporter of all three fossil fuels.

Water consumption by fossil fuel type

Coal

Contrary to my expectations that the water footprint of all fossil fuels has been increasing,

the water footprint of coal decreased because production has been decreasing since 1997 (Figure 1, Figure B1). This may be because the amount of coal reserves has been decreasing or because there has been a shift away from coal consumption as people become more concerned about the environmental impacts of greenhouse gases. The Canadian government has already taken steps to phase coal out in exchange for other sources of energy (Singh and Singh 2012, IISD 2015). However, unlike Canada, the current U.S. government administration does not vow to phase coal out, but rather promotes its use. However, there may still be a decrease in coal extraction and consumption because of energy efficient technologies and a shift to relying on other sources of energy, such as natural gas and renewables (Jenner and Lamadrid 2013).

Oil

I found that oil extraction had the highest water footprint while natural gas had the lowest water footprint in both countries. The water footprint of oil has steadily been increasing from 1968 to 2016, and this is possible because both countries have allowed hydraulic fracturing and can access the shale oil reserves that are buried deeper under the earth (U.S. EIA 2018). However, I found that extracting oil that is deeper under the earth does not necessarily require more water. In-situ extraction uses horizontal drilling to extract bitumen that is too deep to be mined and is far less water intensive than mining, which uses hot water extraction (Wu et al. 2009, Rosa 2016). Also, while I found that secondary recovery accounts for most of the water footprint, the relative percentage of tertiary recovery has been increasing over the years while secondary recovery is decreasing. This could mean that the more water intensive tertiary recovery methods could eventually phase secondary recovery methods out in the future.

However, it is important to note that the water footprint of oil is also rapidly increasing. Although it decreased by 35% from 1985 to 2006, the water footprint increased by 108% from 2006 to 2016 in the U.S. The decrease may be because of the depletion of reserves near the earth's surface until the U.S. developed hydraulic fracturing that allowed them to dig deeper into the earth (EPA 2016). This is further supported by my results because I had found that 2007 is the year that shale oil began to be produced commercially in the U.S., which uses fracking to extract (U.S. EIA 2018b).

Natural gas

Lastly, I found that the water footprint of natural gas has fluctuated greatly over the years, but has continued to increase since 2009 in Canada. The major decreases in the water footprint of natural gas may be attributed to the depletion of conventional natural gas reserves while the increases may result from the development of new fracking technology that allows for increased natural gas production (U.S. EPA 2018). Meanwhile in the U.S., the water footprint of natural gas extraction has increased by 118% from 1990 to 2015. This overlaps with the dates I found coal to have decreased in production, which further proves the point that U.S. producers and consumers may be moving away from coal and looking towards alternative forms of energy.

While natural gas has the lowest water footprint of the three fossil fuels, Canada and the U.S. are major global producers of commercially available shale gas in the world (U.S. EIA 2018b). Oil is extracted the most out of all the fossil fuels currently, but the industry sees increasing potential for the development of natural gas (Grubert et al. 2012). Natural gas will therefore increasingly impact Canada's and the U.S.'s water resources, as the EIA estimated that shale gas production will account for half of all natural gas produced in the U.S. by 2035 (Kobek et al. 2015, U.S. EIA 2018b). My results support this projection because shale and tight gas comprise increasing amounts of the total water footprint for natural gas extraction. Therefore, while the water footprint of natural gas is the smallest as of now, my results suggest that there is an increasing dependence on shale gas that will inevitably increase its water footprint to higher levels. We can visually see that there is a dramatic increase in the water footprint of natural gas after 2005 (Figure 6). The magnitude of change from 1990 to 2005 was only 15% whereas it increased by 89% from 2005 to 2015 in the U.S. This can be attributed to the development and widespread use of hydraulic fracking in the late 2000s that allowed for the extraction of shale and tight gas in both countries (U.S. EIA 2018b).

Water-energy trade by country

Canada

Canada is generally a net exporter of coal, oil, and natural gas, with oil accounting for 96.5%

of the water footprint of energy trade in 2016. However, it has been found that Canada has already begun to see the effects of decreased precipitation and snowfall due to climate change, and future droughts are expected to occur in more regions for longer periods of time at increased severity (Vincent and Mekis 2006, Bonsal et al. 2011). This will affect the amount of fossil fuels they can extract in the future, which in turn affects the countries who rely on Canada's exports. However, a previous case study has shown that the melting of permafrost and decrease of sea-ice cover can increase the mining of fossil fuels because more reserves are exposed (Prowse et al. 2009). Additionally, Canada can transport these resources faster and more efficiently as previously icy roads that needed to shut down operations in the winter will be available to use throughout the entire year (Prowse et al. 2009). It can then be argued that Canada is still a dependable source of energy to some countries who rely on imports.

U.S.

The U.S. has been producing increasing amounts of fossil fuels and are generally exporters of coal and natural gas, but they import large amounts of oil. This large volume of imports suggests that although the U.S. currently has enough water and fossil fuel resources, it is more economically profitable for the country to buy energy from other nations. A previous study has found that the U.S. has been strongly favoring imports over exports due to various factors such as globalization and the need to supply for such a large population (Matthews 2007). However, this reliance on imports can cause many environmental problems because borrowing water from others places the burden of water depletion on producing countries. While I quantified the amount of water the U.S. is essentially borrowing from other countries, previous studies have also studied the impact energy trade can have on greenhouse gas emissions. The U.S. was reported to have produced only 17% of the world's carbon dioxide emissions in 2003, but their total consumption actually accounted for around 24% of global emissions (Soytas et al. 2007). These results therefore show how important it is to examine how much energy the U.S. is importing and calculate the associated costs, such as water consumption, so that policymakers can plan for future supply and demand more accurately. Lastly, trade agreements such as NAFTA has ensured lowered gas prices even when the oil is imported from Canada and Mexico (Destler 2005). The U.S. economy and citizens' access to energy and water are therefore dependent on international supply and relations, which

may be highly variable. I found that the U.S. reached a peak of imports in 2006 and has since decreased their imports by 48% (Figure 14). 2006 is also the year I found U.S. oil production and water footprint to have increased as a result of hydraulic fracturing (Figure 4). These results show that the U.S. is becoming less dependent on imports from other countries, but they will now have to face the burden of water scarcity more within the country.

Limitations and future directions

Like previous studies have found, I found that data in this field is very limited, but the water footprint calculations I obtained in this study provide more specific information about the general magnitude and trajectory of water usage in fossil fuel extraction than past results (Wu et al. 2009, Mielke et al. 2010, Grubert et al. 2012). Another difference from past studies was that I was able to calculate more specific estimates because I was able to delineate the data between more extraction methods while the others did not (Spang et al. 2014). Similarly to past results, I found that natural gas has the smallest water footprint and that oil and coal use more water comparatively (Grubert et al. 2012, Spang et al. 2014).

Future efforts can include urging companies and national governments to be more transparent when they collect and report data. In order to do so, it is important that agencies such as the Global Reporting Initiative and Water Footprint Network first set clear standards on what is considered an input of water and what is not, such as recycled water (Danoucaras et al. 2013). It has been found that mining companies have not been truthful when reporting recycled water usage in an effort to appear more sustainable, so this again urges the need for transparent reporting (Mudd 2008). Lastly, future studies can analyze if projections of future water supply can sustain the current trends of water usage. Based on the results of this study, I concluded that water consumption for energy extraction in Canada and the U.S. However, is important that future studies examine how much water is being used for energy extraction for all the major global producers of energy, such as Saudi Arabia.

Conclusions

The trend of increasing water consumption is particularly alarming as many countries

already face water scarcity and drought conditions will only worsen with climate change. While this issue seems to impact arid and semi-arid countries the most, water scarcity is actually a global issue because these areas are the ones who produce the most energy (Bowden 1975). As I have found in my study, the U.S. is one of the major global producers of oil, yet they themselves are becoming increasingly reliant on imports from other countries. Saudi Arabia is known to be a major exporter of oil, yet their arid climate is extremely vulnerable to drought. Without water, there will not be enough energy to fuel the world, which can give rise to political issues such as governments being unable to provide for basic human rights and conflicts between interregional water rights. Improvements in technology may increase energy production and water efficiency. In my results, I had found that transportation is responsible for most of the water consumption, so future developments can focus on making this process less water intensive. Additionally, developing and studying alternative forms of energy may shift us away from fossil fuels entirely as renewable sources of energy have a lower water footprint than fossil fuels with the exception of biofuels (Spang et al. 2014). Fossil fuels are non-renewable, and although we may have avoided peak coal and peak oil in the past by developing new technology, these methods require a lot of additional resources.

ACKNOWLEDGEMENTS

Patina Mendez and Leslie McGinnis were instrumental in helping me edit this paper and helping throughout the entire process. I also thank Paolo D’Odorico and Lorenzo Rosa for helping me become familiar with this topic and providing me assistance in gathering the data and analyzing the results. Finally, I thank my family and friends for supporting me throughout my years at UC Berkeley.

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APPENDIX A: Water Consumption Values

Table A1: Water consumption values for coal production processes. Estimates and averages were taken from Mielke et al. 2010's study. It was assumed that Canada and the U.S. had similar water consumption values for coal.

Coal production process	Water required (gal/MMBtu)
Mining lower estimate	1
Mining upper estimate	6
Mining weighted average	2.6
Washing lower estimate	1
Washing upper estimate	2
Washing weighted average	0.8
Transportation lower estimate	3.3
Transportation upper estimate	7.2
Transportation simple average	5.25

Table A2. Water consumption values for oil extraction in Canada. These values were taken from Wu et al. 2009's study.

Recovery Phase	Water required (L water/L gasoline)
Primary	0.2
Secondary	5
Tertiary	
• Surface mining lower estimate	5.2
• Surface mining upper estimate	7.7
• In-situ drilling lower estimate	2
• In-situ drilling upper estimate	6.2

Table A3. Water consumption values for oil recovery in the U.S. These values were taken from Mielke et al. 2010's study. Although I only used the values for air injection and CO₂ injection in my study because they are the most common methods, some tertiary recovery methods can become very water intensive.

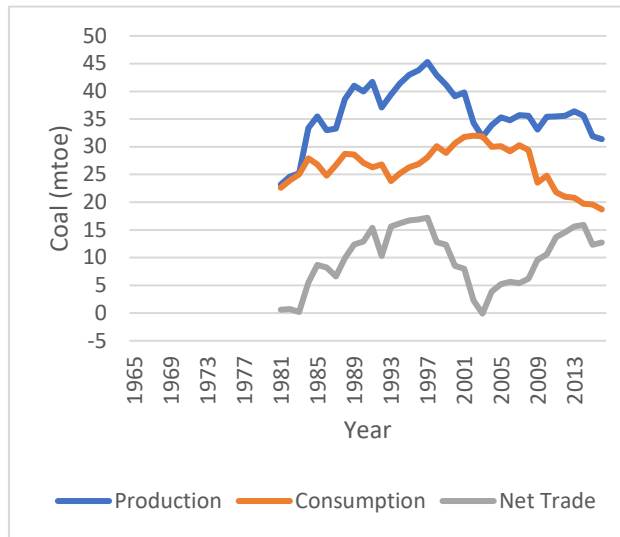
Recovery Phase	Water required (gal/MMBtu)
Primary	1.4
Secondary	62
Tertiary	
• Air injection	14
• Caustic injection	28
• Steam injection	39
• CO ₂ injection	94
• Micellar polymer injection	2,485

Table A4. Water consumption values for natural gas extraction. These values were taken from Mielke et al. 2010's study. I assumed that Canada and the U.S. had similar water consumption values for natural gas.

Process	Water required (gal/MMBtu)
Extraction: conventional/coalbed methane gas	0
Extraction: shale/tight gas	1.2
Transportation (pipeline)	1

APPENDIX B: Fossil Fuel Production, Consumption, and Net Trade

(a)



(b)

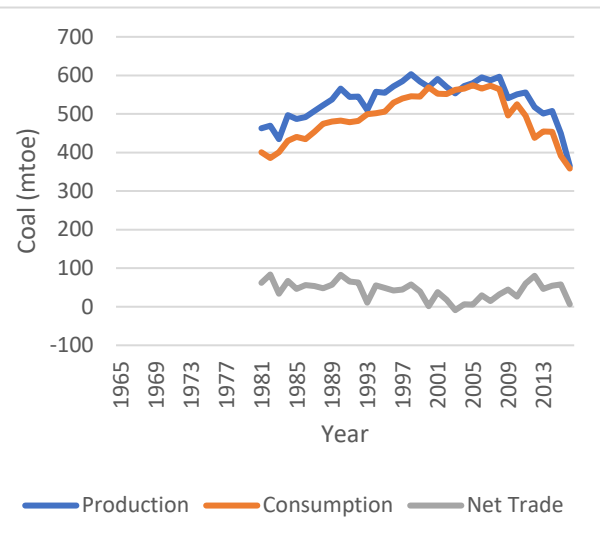
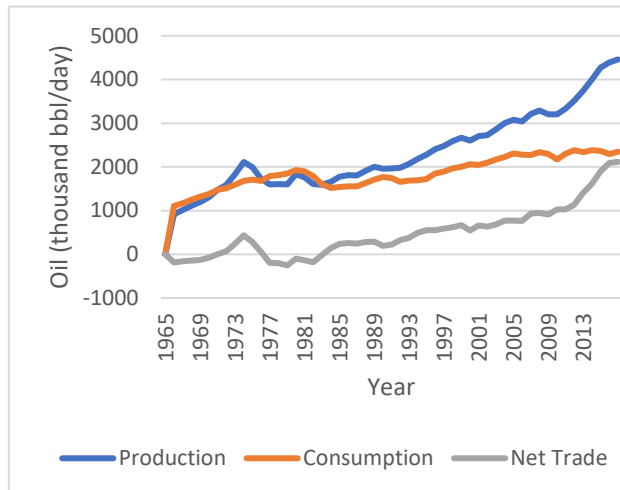


Figure B1: The amount of coal produced, consumed, and traded. I found how much total coal was produced and consumed in (a) Canada and (b) the U.S. and subtracted consumption from production to find how much energy was traded.

(a)



(b)

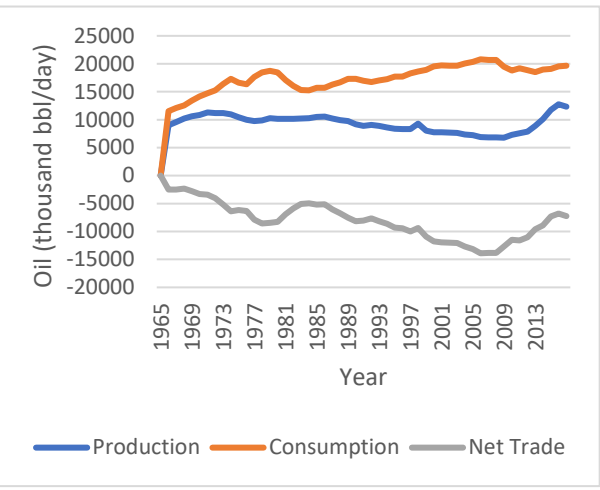


Figure B2: The amount of oil produced, consumed, and traded. I found how much oil was produced and consumed in (a) Canada and (b) the U.S. and subtracted consumption from production to find how much energy was traded.

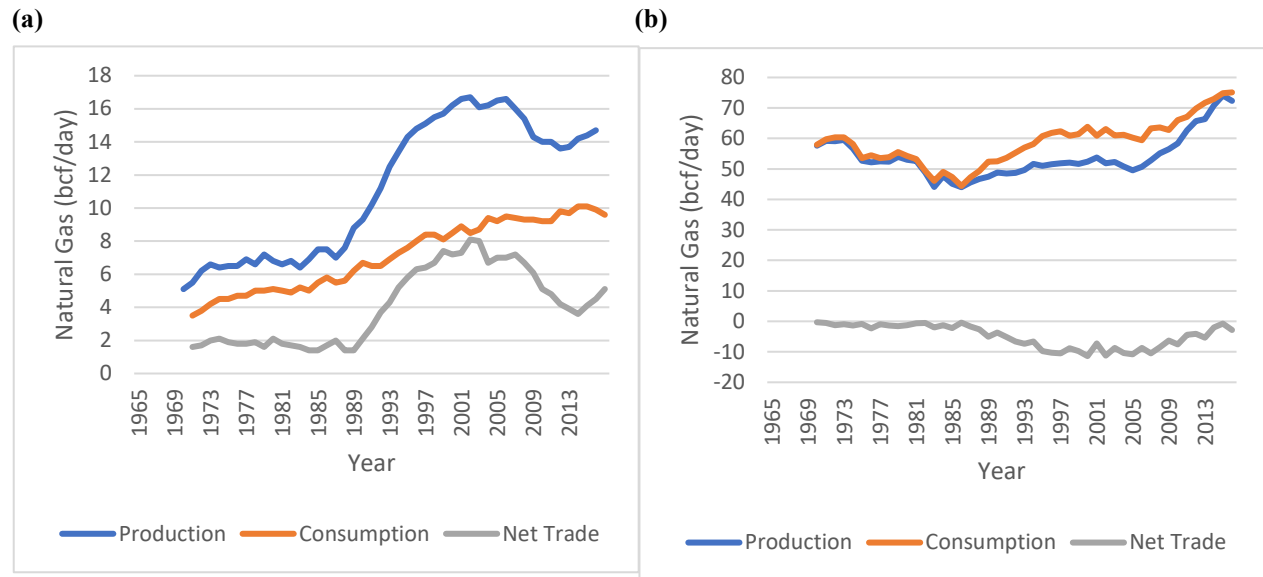


Figure B3. The amount of natural gas produced, consumed, and traded. I found the amount of total natural gas that was produced and consumed in (a) Canada and (b) the U.S. I then calculated the net trade of natural gas by subtracting the amount of energy consumed from the amount produced in each country.