Comparative Analysis of Methane Emission from Energy Sources in Azerbaijan, Kazakhstan, and Russia

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Abstract

Methane is an important greenhouse gas standing as a potential threat to climate by contributing to global warming. Numerous studies conclude that in terms of its warming potential, methane is 86 times more powerful than carbon-dioxide although its lifespan in the atmosphere is much shorter than CO_2. It is reported that methane concentration in the atmosphere has increased more than 2.5 times compared to the figures of pre-industrial periods and 30% of the rise in global temperature is attributed to methane leakage related activities. However, increasing concentration of greenhouse gas in the atmosphere has not received sufficient attention from the global community excluding recently accepted conventions and agreements. In this study, methane emission from energy sources is comparatively analyzed in the example of Azerbaijan, Kazakhstan, and Russia. Based on both primary and secondary data, emission sources are identified. By employing Multiple Linear Regression analysis, effects of 4 explanatory variables on methane emission from energy sources are tested. Regression results indicate that in Azerbaijan, total oil and natural gas production, coal consumption, and natural gas flaring positively contributes to methane emission while hydroelectricity generation demonstrated no significant effect. On the other hand, total oil and natural gas production, coal consumption, and hydroelectricity generation indicate positive effect on CH_4 emission for Kazakhstan whereas no significant effect of natural gas flaring is found. Finally, regression analysis concludes that all three tested variables have positive effect on methane emission from energy sector in Russia; however, the effect of natural gas flaring could not be tested since official data is not available for Russia. Additionally, the study also presents various mitigation techniques regarding the emission of greenhouse gas.

Keywords: methane emission, energy, oil, natural gas, flaring, coal, hydroelectricity

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List of Abbreviations

AAAS	**American Association for the Advancement of Science**
AGU	**American Geophysical Union**
BP	**British Petroleum**
CAPP	**Canadian Association of Petroleum Producers**
COP21	**United Nations Climate Change Conference**
EDF	**Environmental Defense Fund**
EPA	**Environmental Protection Agency**
FAOSTAT	**Food and Agriculture Organization Corporate Statistical Database**
GDP	**Gross Domestic Product**
IEA	**International Energy Agency**
IGSD	**Institute for Governance & Sustainable Development**
IPCC	**Intergovernmental Protection Agency**
NASA	**National Aeronautics and Space Administration**
NCEI	**National Centers for Environmental Information**
NOAA	**National Oceanic and Atmospheric Administration**
NRDC	**Natural Resources Defense Council**
SLCPs	**Short Living Climate Pollutants**
SOCAR	**State Oil Company of Azerbaijan Republic**
UN	**The United Nations**
UNCCC	**United Nations Climate Change Conference**
UNFCC	**United Nations Framework Convention on Climate Change**
WSJ	**The Wall Street Journal**
YCCC	**Yale Program on Climate Change on Communication**

Introduction

July 2023 has been recorded as the hottest month in Earth's history for the last 120,000 years as several countries, such as China, Japan, Spain, and Italia, recorded their all-time warmest temperature figures (The Washington Post, 2023). Consequently, climate change and global warming have turned into two of several main phenomena that humanity is struggling to stop and minimize even in the 21st century, in a period of advanced tools, technology, and machinery. In its press summary published in 2023, *Environmental Defense Fund* reports climate change and global warming as undeniably important events that cause serious risks towards health of living species (mainly for humans), water supply, and the whole agricultural system (EDF, 2023). During recent years, these two events have also drawn significant attention from the global community. In December 2015, for example, Paris Agreement has been adopted by 196 parties in *United Nations Climate Change Conference* which is also known as COP21 (UN Climate Change, 2023). Adoption of Paris Agreement, whose aim is to limit increases in global temperature below 2°C above pre-industrial levels, signs a milestone in fighting against climate change and its negative effects because as stated by UNCC, it is the first legally binding agreement that brings all nations in the world towards serving a uniformed purpose through economic and social transformations and developments. In addition to the vitality of adoption of Paris Agreement in combating climate change, science experts and writers from *National Oceanic and Atmospheric Administration*, David Herring, and Rebecca Lindsey, also highlight importance of significant and urgent actions by global community to minimize effects of climate change and global warming. Experts claim that without taking dramatic actions immediately, achieving overarching goal of COP21 does not seem feasible and realistic (NOAA, 2022).

Before discussing the main causes and effects of global warming and climate change, it is important to define these concepts. *The Journal of National Geographic* defines global warming as an ongoing and sustaining increase in the level of average temperature on Earth (2023). Annual Global Climate Report, another important source of climate information, is a yearly summary release that reports year-long global warming activities and relevant statistics. Published by *National Centers for Environmental Information*, an institution that collects and reports environmental data and publishes relevant research studies, the climate report also indicates annual average global temperature for ocean and land surfaces. Global average temperature for ocean and land surfaces has been initiated to be recorded starting from 1880. An interesting, yet striking, point is drawing attention in an updated version of the report published in 2022. That report emphasizes that based on the last 140 years' annual average global temperature statistics, the warmest 10 years took place after 2010. Supported by the below-given illustration (Figure 1), this signs an obviously growing global warming problem that must be managed (NCEI, 2022).

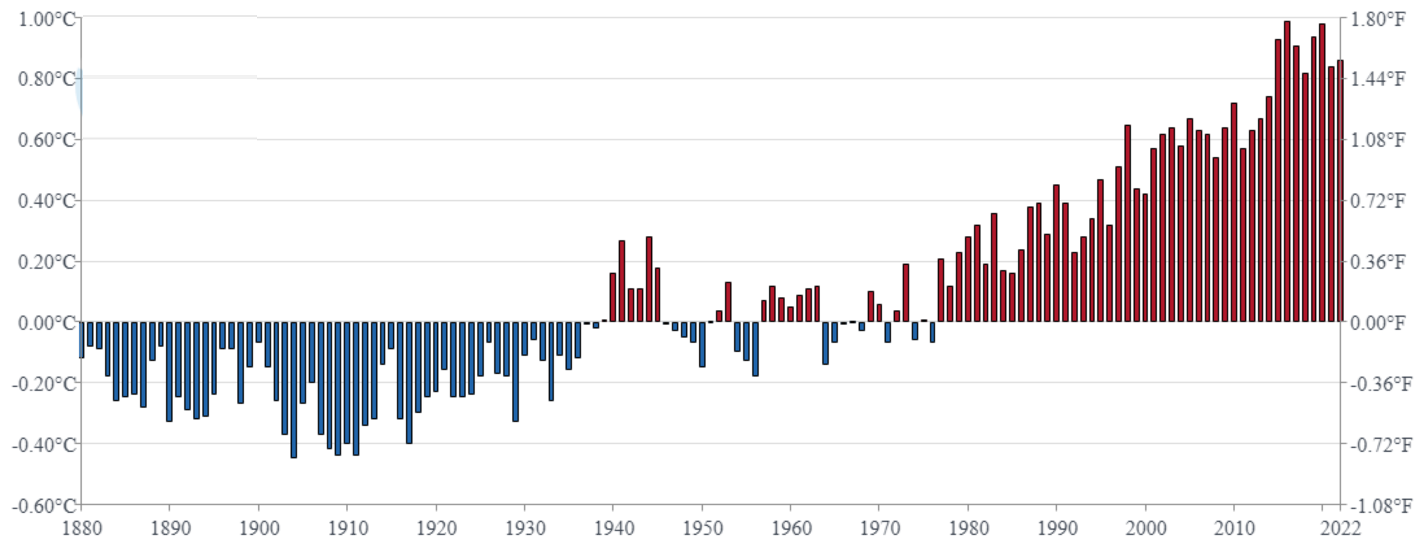


Figure 1: Global Land and Ocean, January-December Temperature Anomalies

On the other hand, *the United Nations* defines climate change, another important concept of this context, as an observed change in long-term patterns of weather and temperature (UN, 2023). In its chronicle published in 2007, *United Nations* points out that negativities observed on human health, faster increase of rise in the sea level, higher occasions of flooding and drought accidents, loss of various animal species, and many other numerous distortions in the environment recorded as negative externalities are caused by the presence and acceleration of climate change (2007). The chronicle presents climate change as a major threat to human health by referring to the statistics of the *World Health Organization*. It reports that climate change itself is responsible for 150,000 human deaths annually and this figure is estimated to double by 2030. Overall, climate change and global warming stand as serious threats to the existence of humanity and sustainability of life on Earth by possessing serious catastrophic effects to the environment and living species. Some of many examples of these effects are listed as infectious diseases, heatwaves, loss of agricultural productivity, and an increase in the spread of asthma and other respiratory diseases (UN, 2007).

Understanding the severity of the threats from climate change and global warming, implementing actions to cease these threats has been turned into a mission of humanity. Therefore, as an important part of a solution, several studies have been dedicated to analyzing main factors and activities that trigger the presence and increase of these occurrences. In order to take not only effective, but also efficient actions to lower negative effects of these events and to attain global-level climate goals such as Paris Agreement's, offering relevant policy alternatives, establishing required industry standards, and defining direct and indirect causes of global warming and climate change is a critical milestone to achieve. While highly important and versatile global-level actions are consistently conducted to serve environmental purposes, in order to maintain a sustainable life on Earth and minimize above-mentioned negative externalities caused by climate change and global warming, there are still more milestones to achieve. For example, in 2022, *The World Bank* spent approximately 31.7 billion dollars to support climate-related projects and initiations of countries (The World Bank, 2023). While this figure invested by the largest multilateral climate supporter is all-time highest record among all the organizations that provide financing towards climate action (19% higher than the amount spent in 2021, 26.6 billion dollars), it is only a small fraction required to achieve climate targets of Paris Agreement. So, *The Wall Street Journal* published their estimated amount of investment requirement to meet important climate targets as limiting global average temperature to 1.5 degrees Celsius above pre-industrial periods'. It is reported that 131 trillion dollars is an approximate estimate (The Wall Street Journal, 2021). It turns out that the all-time highest amount spent towards climate actions (31.7 billion dollars by The World Bank) is only 0.02% of the WSJ estimate.

Having talked about the global efforts and investments directed into the issue, as it is highlighted earlier in this paper, in order to achieve a substantial decrease at the level of climate problems, understanding the main causes is a crucial step since incomplete or inaccurate understanding and recognition of contributing factors might result in misguided and inefficient efforts whose output might end up being tactless policy alternatives, falsely-established industry standards, and eventually, wasted investments. Therefore, exploring root causes of climate issues has been an extensively analyzed topic of rigorous studies.

Talking about the found contributors to the climate issues, *American Association for the Advancement of Science* revealed that based on their global observations, climate change is a doubtlessly ongoing problem. It has also been found that main driving contributors of this problem are associated with anthropogenic activities rather than natural occasions (AAAS, 2009). *The Natural Resources Defense Council* emphasizes air-polluting gases as the main reason for global warming and climate change. As a result of air-pollutant gases' emissions to the atmosphere, absorption of solar radiation and sunlight in the atmosphere occurs which results in the increase in the surface temperature (NRDC, 2022). In academic literature, these air pollutant gases are usually defined as *greenhouse gases*. Increase in the concentration of greenhouse gases in the atmosphere is known to be the main reason of an ongoing global warming problem (Al-Ghussain, 2018). Additionally, another study published by *American Geophysical Union* has also demonstrated consensus with prior studies by highlighting that emission of greenhouse is the only dominant alternative reason to the ongoing global warming problem since 1950s (AGU, 2019).

Since we have narrowed down the root cause of climate-related problems to the emission of greenhouse gases as a result of human-driving activities, specific elements of greenhouse gases can also be analyzed, and available academic studies contain numerous examples in this regard. As an independent executive organization missioned in sustaining healthy life on Earth, *United States Environmental Protection Agency* defines greenhouse gases as the ones that are stored in the Earth atmosphere and increase its overall average temperature (EPA, 2023). Greenhouse gases include gases such as carbon-dioxide (CO_2), methane (CH_4), dinitrogen-oxide (N_2O), halocarbons and SF_6, and molecular hydrogen (H_2) (World Meteorological Organization, 2023). Increasing usage of fossil fuels in the 21st century is an important factor triggering an increase in the overall Earth temperature. As a result of fossil fuel overuse, greenhouse gases are emitted to the atmosphere which ends up increasing the global overall temperature and causing global warming (EPA, 2023).

Although the emission of greenhouse gases is commonly recalled as a whole in the context of analyzing reasons of global warming and climate change, it is important to break it down into its elements since proportion of the emission volume of specific gases are not evenly distributed in the atmosphere as well as their impact as hazardous gases in the atmosphere. According to the press release, *Overview of the Greenhouse Gas Emissions*, published by the *US Environmental Protection Agency*, carbon-dioxide (CO_2) emission has the largest portion among emissions from all greenhouse gases by approximately 80%. Following CO_2, methane (CH_4) emission has the second largest portion among emissions from all greenhouse gases at around 11.5%. Dinitrogen-oxide (N_2O), HFCs, PFCs, SF_6, and NF_3 are other elements of all greenhouse gas emissions in the atmosphere by their total portion of 9% approximately (Figure 2).

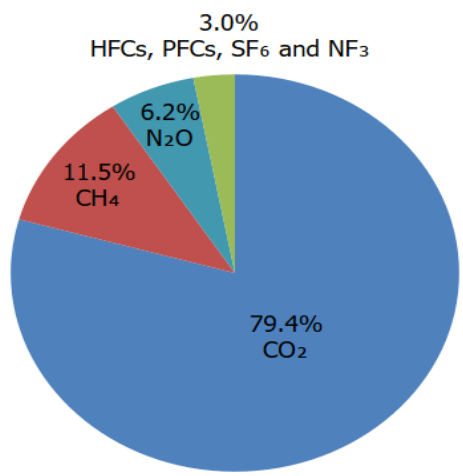


Figure 2: Inventory of U.S., Greenhouse Gas Emissions and Sinks: 1990-2021

Since carbon-dioxide emissions have the largest proportion among all other greenhouse gases, comprising 80% of all the greenhouse gas emissions, numerous studies have been conducted to analyze specific effects of carbon-dioxide on global warming and climate change.

To recall some of these studies from academic literature, in their study published in 2020, Yolo and Dramora explain the positive contribution of carbon-dioxide emission on global warming and climate change. By focusing on the environmental impacts of carbon-dioxide on climate change and global warming, the study offers multiple solutions for the mitigation of carbon-dioxide emission based on specific industrial sectors such as power, iron, steel, cement, and petrochemical sectors. This study also presents long-term trend analysis for carbon-dioxide emission statistics starting from the first industrial revolution which took place in the middle of 18th century (Yolo et al, 2020). In another study conducted in 2008, Georgios A. Florides and Paul Christodoulides analyze the effect of carbon-dioxide emission on average temperature and the potential importance of carbon-dioxide in stimulating growth of living species on Earth. The authors conclude that although beneficial effects of carbon-dioxide are detected in incentivizing growth of living species, increasing concentration of carbon-dioxide in the atmosphere also results in higher surface temperature which is recalled as the *global warming effect* (Florides et al, 2008). Another outstanding example from academic literature is a study conducted by Dr. Sarvar Gurbanov. In his study, analyzing the case of Azerbaijan, he explored the role of natural gas consumption in the reduction of CO_2 emissions. The author noted that while global energy consumption constitutes 73% of anthropogenic greenhouse gas emissions, emissions associated with CO_2 are found to be 75% of the total volume (Gurbanov S., 2021).

As above-given examples from academic literature support the hypothesis that carbon-dioxide emission exhibits positive effect on global warming and climate change, studies and investment on the mitigation of carbon-dioxide emission to the atmosphere are supported by various means. However, an important question arises if carbon-dioxide is the only important greenhouse gas causing climate change and global warming among all different greenhouse gases such as methane, dinitrogen-oxide, and fluorinated gases. The answer to this question is the main motive of this study which is going to be elaborated further during this paper.

Carbon-dioxide has been the main focus of the investigations while analyzing anthropogenic impact to climate change. *Intergovernmental Panel on Climate Change* (IPCC) informs that emission of carbon-dioxide is, indeed, the main human factor contributing to the climate change (2007). On the other hand, as the second largest anthropogenic contributor to climate change, methane is also a critical factor to be analyzed in estimating human-made contribution to climate change and global warming. Although it is accepted as a hazardous greenhouse gas that contributes to climate change and global warming, existing literature hardly discusses comparative analysis of methane emissions, also known as methane leakage, across various countries (Andrew et al, 2010). First of all, as being informed about the contribution of carbon-dioxide emission in triggering global warming and climate change, a similar understanding must be acquired regarding the methane emission as well. Currently, there are examples of academic studies and official government and agency reports comparing the hazardous impact of methane emissions on global warming and climate change against that of carbon-dioxide. To understand the significance of methane emission in damaging the environment, the following paragraph from *International Energy Agency's* press release, *Global Methane Tracker 2022*, is essential. The press release discusses that methane is often compared to carbon-dioxide in terms of its effect on climate change. In rationalizing this comparison between carbon-dioxide emission and methane emission, IEA highlights two key features of greenhouse gases that must be evaluated if its impact on the climate is to be figured out. The first feature is how long can a greenhouse gas stay in the atmosphere which is the *lifetime of the greenhouse gas*. In this regard, methane is found to have a much shorter lifetime than carbon dioxide. While methane can remain for only 12 years in the atmosphere, carbon-dioxide does so for centuries. Secondly, greenhouse gases' impact on climate is evaluated based on their *energy absorbability* which shows how much energy a certain greenhouse gas can store in the atmosphere. It is revealed that methane has a larger energy absorbability than carbon-dioxide. So, although methane has a much smaller lifetime value in the atmosphere, it absorbs a bigger volume of energy than carbon dioxide. Air quality is also damaged as a result of methane emission process which later leads to tropospheric ozone pollutant and explosive hazards (IEA, 2022).

Moreover, in terms of understanding the effect of methane emissions in contributing to global warming and climate change on Earth, an official press release published in 2021 by the *Canadian Government* is highly important and informative. The release summarizes that in terms of warming potential, methane is 86 times more powerful than carbon-dioxide (Government of Canada, 2021). All this information from different official sources about the methane emission ends up with a conclusion that in order to minimize environmental damage, emission from non-carbon-dioxide gases (especially, methane) must also be managed effectively.

As a result of above-mentioned various study materials and official press releases, it is inferred that in order to lower the volume of ongoing global warming and climate change activities, achieving reduction in methane emissions is a critical point supported by various official sources. Although focusing on achieving a reduction in carbon-dioxide emissions is a critical step towards ceasing global warming and climate change, this is not the only effective and efficient way of achieving this mission. In its May 2022 press release, *The Guardian* narrated that according to the scientists, ignoring hazardous effects of other greenhouse gases and focusing solely on reducing CO_2 emission will not help to achieve controlling global warming within the limit of 1.5°C by confirming the fact that warming power of methane is 86 times higher than the warming potential of carbon-dioxide (The Guardian, 2022). In an interview to *The Guardian*, Professor Durwood Zaelke, the president of the Washington-based *Institute for Governance and Sustainable Development* (IGSD) claimed that focusing solely on decarbonizing and stopping short-lived climate pollutants (SLCPs) reduction practices will increase the global temperature by 2°C which is the upper limit determined in Paris Climate Agreement in 2015 (The Guardian, 2022). In addition to this, Dr. Gabrielle Dreyfus, chief scientist for the IGSD, elaborated on the importance of reducing non-CO_2 pollutants by stating that while only CO_2 reduction is estimated to lower down the global temperature by 0.07°C by 2050, reducing emission of non-CO_2 pollutants is estimated to lower down the global temperature by 0.26°C for the same timeframe, and this outcome is estimated to be four times more effective than focusing on CO_2 reduction solely. Furthermore, Dreyfus also added that by 2050, combined with the de-carbonization activities, pursuing abatement in non-CO_2 pollutants, mainly methane, would lower down the global warming by 50%. Therefore, potential effects of non-CO_2 pollutants in global warming should not be underestimated by the scientists and governments should take SLCPs effects into consideration while forming public policies to stop global warming. (The Guardian, 2022).

In its 2022 Overview of Global Methane Tracker, *International Energy Agency* also reported that reduction in an increasing global average temperature is perceived to be achievable along with its importance, and dealing with the emission of methane is a critical part of accomplishing this reduction. The agency reported that current methane concentration in the atmosphere is the peak point during the last 800,000 years and it is accountable for 30% of observed global warming up to date (IEA, 2022). Although hazardous effect of methane as a greenhouse gas to the climate is well-known and supported by various studies, no significant outcome has been achieved in lowering the methane concentration in the atmosphere (Figure 3). *National Aeronautics and Space Administration* reports that during the last two centuries methane concentration in the atmosphere indicated 200% increase which is also associated with the 20 to 30% of the global warming happening since Industrial Revolution (NASA, 2023).

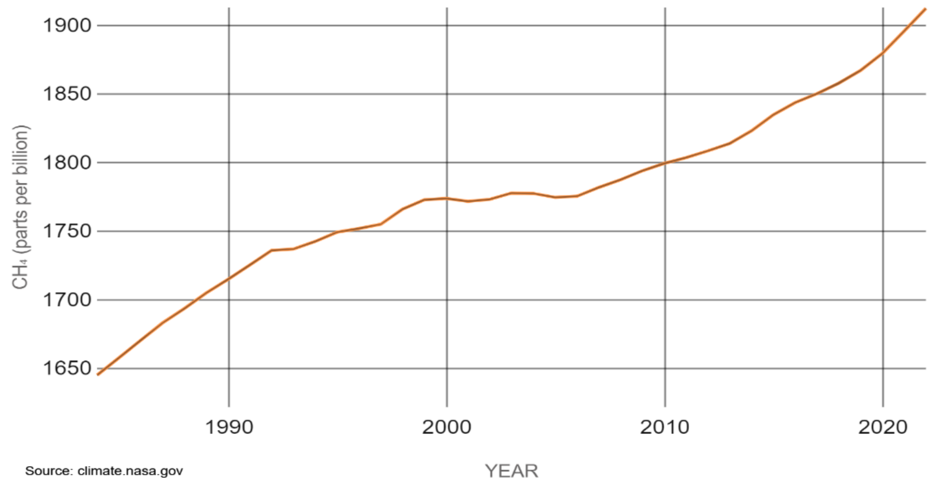


Figure 3: Atmospheric methane concentration since 1984

In 2021, 135 million tons of methane is emitted by the energy sector only, and this is 5% higher than 2020 figure (Figure 4). Global Methane Tracker identified China (28 million tons) as the biggest emitter of methane considering energy sector related activities such as oil & gas operations and coal activities. Russia and USA follow China with 18 and 17 million tons respectively (IEA, 2022).

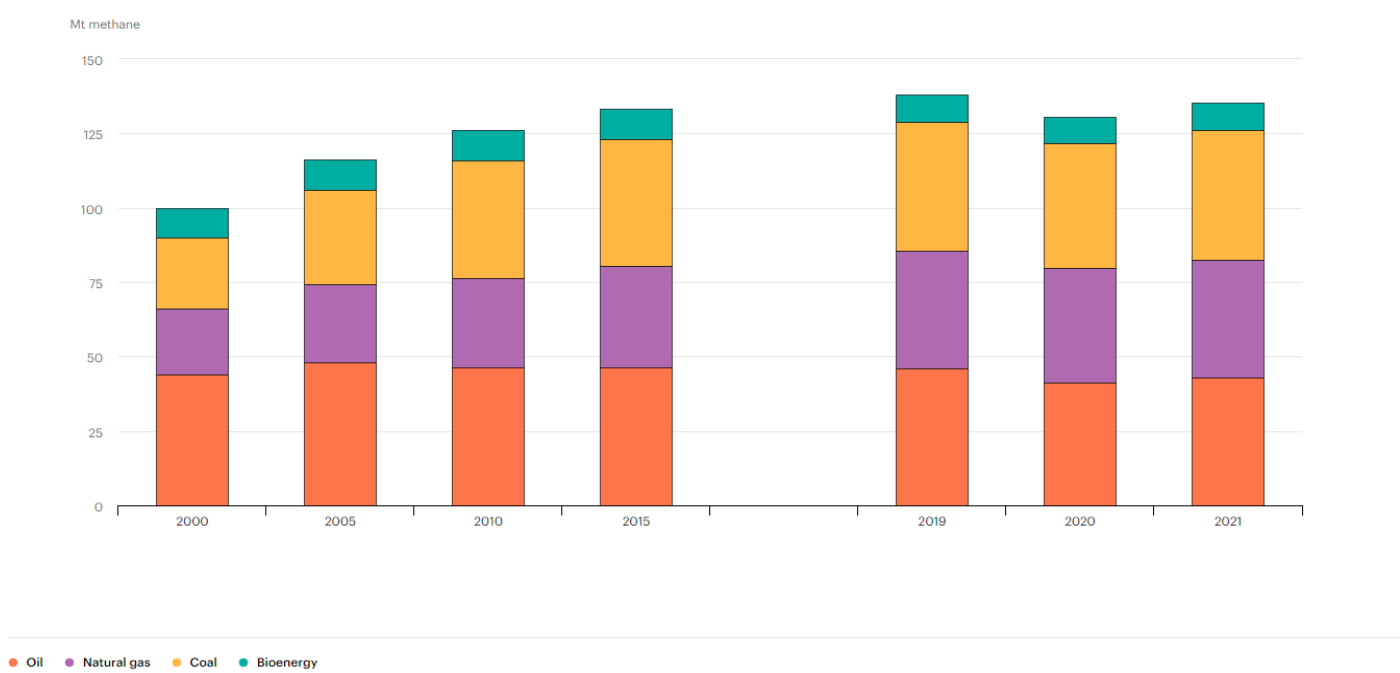


Figure 4: Global Methane Emission from Energy Sector, 2000-2021

Scientific evidence indicates that methane leakage is caused by both natural and human-related factors. According to the study conducted by Izzet Karakurt and his colleagues, 40% of the annual total methane emission is attributed to natural sources such as wetlands, water reservoirs, and ponds. On the other hand, the majority of the methane leakage is sourced from anthropological activities such as mining, oil and gas production, agricultural activities, waste combustion, and so on (Karakurt et al, 2011).

Although anthropogenic methane leakage is occurring from various sources, methane emission from energy, industry, agriculture, and waste sectors are the most outstanding fields in terms of the volume of methane emitted to the atmosphere (Karakurt et al, 2011). In their study of anthropogenic methane emission analysis by sectors, Izzet Karakurt and his colleagues found that the agriculture sector is the biggest emitter of anthropogenic methane emission. Additionally, the study remarked that energy, industry, and waste sectors are respectively the second, third, and fourth largest sectors that human-made methane emission is attributed to.

As it is the second largest emitter of anthropogenic methane emission, this paper will focus on the analysis of methane emission from energy sector in the example of three specific countries (Azerbaijan, Kazakhstan, Russia). Furthermore, it should also be noted that the sector selection of methane emission is also related to the selection of countries analyzed in this paper since selected countries are major participants in the energy market.

Consequently, this study will discuss a comparative analysis of methane emission from energy sector in the example of Azerbaijan, Kazakhstan, and Russia. The justification for country-specific selection is based on several factors common to all three countries.

First of all, these countries are consistent emitters of methane, CH_4. *Global Methane Initiative* is a public-private partnership specialized in providing methane-related statistics, projections, and policies oriented to use methane as an effective energy source. In their report published in 2023, Global Methane Emissions and Projections, consistent emission of methane is visualized and reported. As depicted in Figure 5, although each country indicates a different level of increase, starting from 1990, methane emissions from energy sectors of these countries demonstrate an upward trend (Global Methane Initiative, 2023). Since methane emission from energy sector is a consistently increasing trend for these countries, analysis of this phenomenon is highly important for reducing further and potential environmental hazard as supported by the previously mentioned studies regarding potential effect of methane emission reduction in ceasing global warming and climate change.

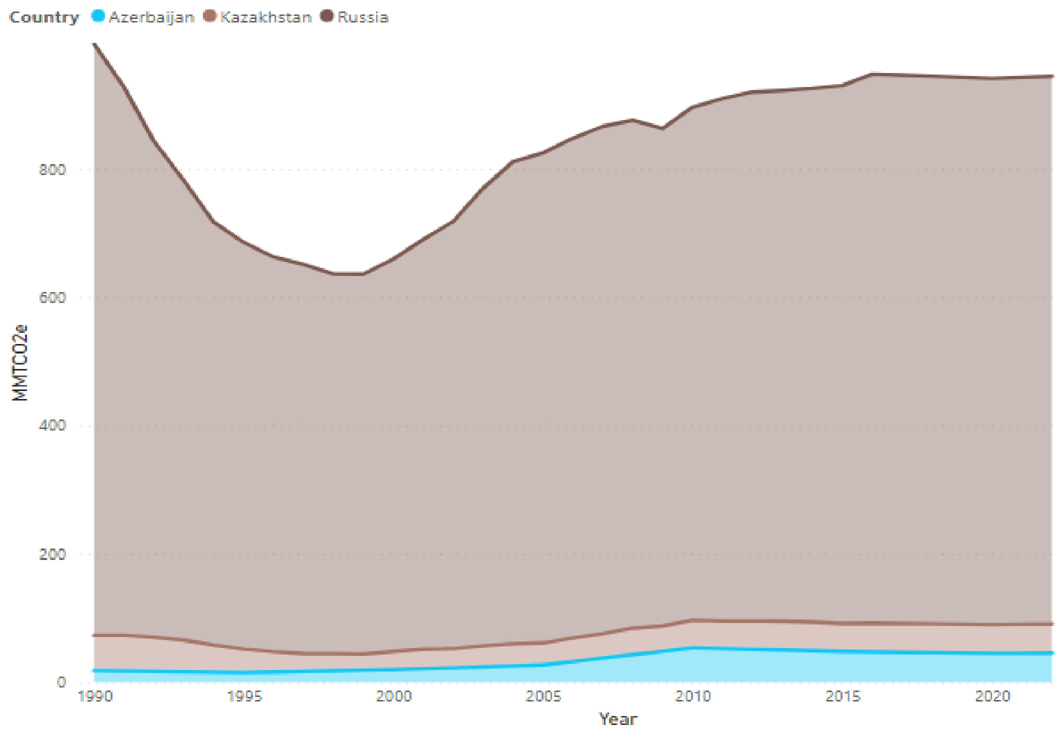


Figure 5: Annual methane emission volume from energy sector by countries, 1990-2022

The second factor for country selection is based on the countries' activity in oil and gas production. These three countries are among the largest participants in the world's energy sector, especially in the oil and gas market. According to the 70th edition of the Statistical Review of World Energy published in 2021 by *British Petroleum*, Russia, Kazakhstan, and Azerbaijan are among the top 20 countries (6th, 12th, 19th respectively) in terms of the available oil reserves (World Population Review, 2023). On the other hand, considering the volume of oil production, measured in barrels per day, these countries are listed in top 25 globally (3rd, 18th, 24th respectively) (FAOSTAT, 2023). Additionally, these countries are also listed among the 25 largest countries in terms of the available natural gas reserves (1st, 15th, 25th respectively) (BP Statistical Review of World Energy, 2023). In terms of natural gas production, measured in million cubic feet, Russia, Kazakhstan, and Azerbaijan are also distinguished among all other world countries (2nd, 24th, 31st respectively) (FAOSTAT, 2023). So, considering the fact that oil and gas industry is responsible for a significant volume of methane emission every year (CAPP, 2023), analysis of countries that demonstrate an active economic performance in oil and gas industry is a rational and justified selection in order to find out main activities that result in methane emission. Furthermore, country-specific revenues from oil and gas production constitutes significant portion of GDP for Azerbaijan (World Economic Forum, 2016), Russia (Le Monde, 2023), and Kazakhstan (Heritage, 2023).

Lastly, none of the selected countries is a member of the *Global Methane Pledge* (US Department of State, 2022). To incentivize national and global level actions to cease methane emission, on November 26, 2021, *Global Methane Pledge* which includes 150 countries was launched by cooperation of The United States and European Union. Member countries are statistically responsible for 45% of the global anthropological methane emission. Considering emission from all the sources, 50% of the global methane emission is attributed to the top 5 methane emitters (China, India, United States, Russia, and Brazil). Out of these 5 countries, only United States and Brazil are the members of the Global Methane Pledge (Global Methane Pledge, 2023). To put in a nutshell, comparative analysis of methane emissions from energy sector in the example of non-member (of pledge) countries is expected to provide insightful results, comparison points, and recommendations for further actions to cease environmentally harmful effects of the greenhouse gas.

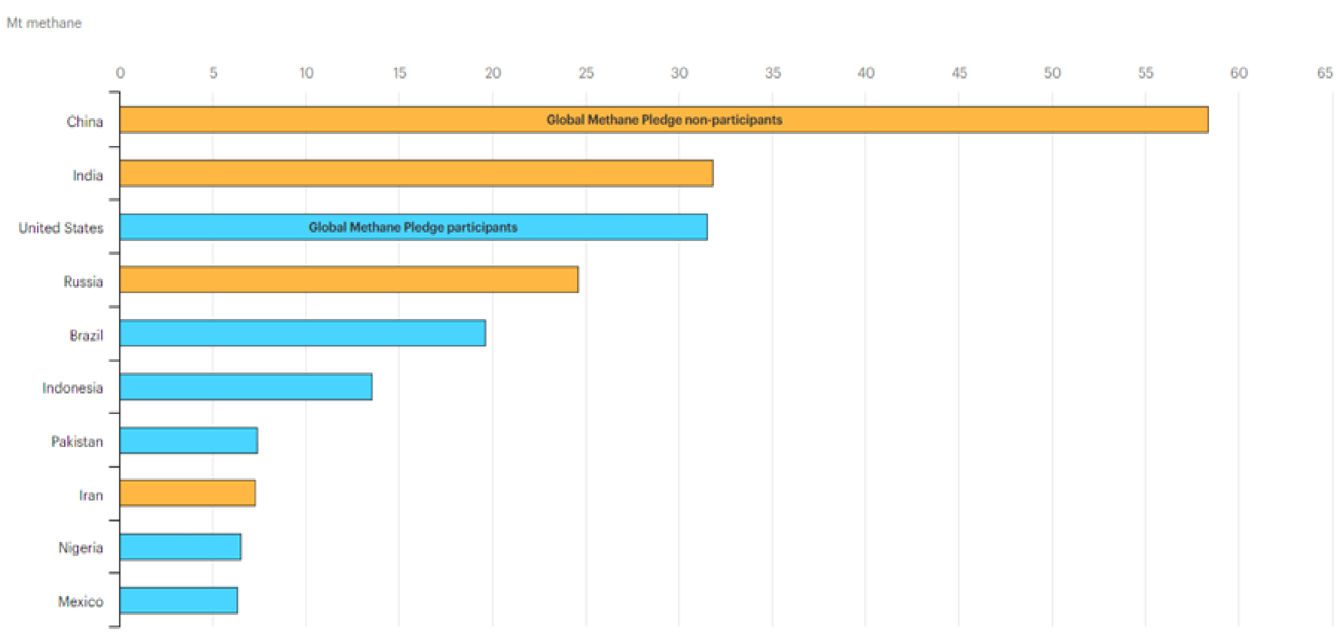


Figure 6: Top 10 emitters of methane, 2021

To summarize the reasons of justification for country selection, all three countries, Azerbaijan, Kazakhstan, and Russia are:

1. Active emitters of the greenhouse gas methane.
2. Outstanding participants in the energy market.
3. Not members of the Global Methane Pledge.

In the following chapter, examples from academic literature are presented, summarized, and discussed. Based on the available studies, research hypotheses are established whose significance will later be analyzed in the *Results* section. Moreover, dependent, and independent variables of this study will be introduced and elaborated in detail by focusing on the selected timeframe and measurements methods of these variables exemplified by literature materials.

Literature Review

In this section of the paper, specific examples of academic studies from literature which focused on the analysis of the causes of anthropogenic methane emissions (focusing on the energy sector) are summarized. Analysis of the numerous examples from academic literature concludes that considering methane emission from energy sector, five main emission sources appear to be highlighted as significant: natural gas production, oil production, coal production, stationary and mobile combustion, and biomass combustion.

In the first study, *"Assessing the causes of anthropogenic methane emissions in comparative perspective, 1990–2005"*, published in 2010, Andrew Jorgenson and Ryan Birkholz explored causes of anthropogenic methane emission. Authors start by arguing that although methane is accepted as a hazardous greenhouse gas that contributes to climate change and global warming, existing literature hardly discusses comparative analysis of methane emission across various countries. It is noted that despite the fact that some examples of cross-sectional studies are available, they fail to provide robust, valid, and reliable results due to incompetence of cross-sectional study techniques. In this matter, authors of the study highlight incompetence of the available cross-sectional studies from two different perspectives. Firstly, cross-sectional data analysis is not proven to be effective in estimating interaction between explained and explanatory variables. Secondly, cross-sectional studies contain heterogeneity issues in which effect of time-invariant factors are dismissed. So, in their study, the strength, and magnitude of the relationship between dependent and independent variables are also tested along as well as the direction of this relationship. Based on 15-years' historical methane emission figures, this study estimated anthropogenic determinants of methane emission by employing fixed effects model panel data analysis technique. Population, economic development, domestic cereal production, cattle, oil and natural gas production, country's reliance on exports in fuels, and country's reliance on exports in food commodities are selected as independent variables. The last explanatory variable is indicated as a percent of the country's total exports. With a total sample size of 596, 4 unbalanced cross-national panel datasets have been included in the model. Authors selected panel data as a preferred analysis technique since it allows us to analyze interactions not only between explained and explanatory variables, but also their interaction with time. Authors justified their selection of fixed effect model in analyzing the panel data by stating that considering its advantage to deal with the heterogeneity bias which is time-invariant (Greene, 2000). Moreover, fixed effect model also helps to reduce false-causality cases in which strong correlation figure between the dependent and independent variables is accepted as a cause of the change in the dependent variable (Allison, 2009). As a result of this study, authors concluded that all these variables, population, economic development, volume of domestic cereal production, cattle, oil, and natural gas, and the country's reliance on food commodities, have a positive effect on the volume of methane emission. Only a country's reliance on fuel exports exhibited statistically insignificant results. In addition, the research also found that magnitude of the effects of certain variables on the volume of methane emission declined across time whereas effects of other variables indicated very stable performance in terms of the magnitude of their effects on the volume of methane emission. To summarize these findings, while positive effects of total population, natural gas production and oil production indicate stable magnitude across time, GDP per capita, cereal production, and cattle production indicate positive effects on methane emission whose magnitude decline across time. The study is concluded by authors' final remarks on the limitations of the available panel data regarding methane emission. This limitation prevented authors from analyzing other possible anthropogenic reasons of the methane emission (Jorgenson et al, 2010).

The next study, published in 2012 by Izzet Karakurt and his colleagues, examines potential anthropogenic causes of methane emission. This study categorizes anthropogenic methane emission results by four different sectors and provides insights and mitigation strategies for each specific sector. According to this study, 60% of the current methane emission is attributed to human-related factors whereas 40% is caused by natural sources. Based on the methane emission data of 20 years (1990-2010) obtained from the *United States' Environmental Protection Agency*, 4 different sectors are analyzed in this research: *agriculture, energy, waste,* and *industry*. The study finds out that the highest portion of the anthropogenic methane emission is caused by agricultural activities. By its approximate proportion of 51% of total human-related methane emission, annually, 3135.75 million tons of methane (in terms of carbon-dioxide equivalent) is found to be emitted to the atmosphere from agriculture sector through activities such as enteric fermentation, rice cultivation, and manure management. Following the agricultural sector, the energy sector is the second largest sector emitting methane from anthropogenic sources with a portion of 28.65% of total anthropogenic methane emission. Operations in the oil and gas industry, coal mining activities, biomass combustion, stationary combustion, and mobile combustion are main causes of emission from this sector. It was also reported that according to the analyzed data, although methane emission from operations in oil and gas industry, biomass combustion, stationary combustion, and mobile combustion increased over time, methane emission from coal mining activities exhibited a declining performance for the same time period. As a result of activities such as landfilling of solid waste and wastewater, by its portion of 20.61%, waste sector is found to be the third largest source of anthropogenic methane emission following agriculture and energy sectors. Additionally, methane emission from these sources indicated a relatively declining trend during 1990-2010 whereas total volume of methane emission from other sources of waste sector increased in this timeframe. Finally, industry-related methane emission is not analyzed in this research due to the significantly lower volume of total methane emission from industry sector compared to the other sectors (Karakurt et al, 2012).

In another study published in 2012, "*Analysis and Mitigation Opportunities of Methane Emissions from the Energy Sector"*, considering the fact that energy sector is the second largest emitter of anthropogenic methane (Karakurt et al, 2012), G. Aydin and his colleagues analyze sources and mitigation opportunities of methane emission from energy sector by focusing on revealing major methane emitting processes in the energy sector and determining specific countries that play the largest contributing role to the methane concentration increase in the atmosphere. In the end, authors provide specific emission mitigation options and strategies for oil-gas and coal production activities. Confirming previously conducted studies in the same field, authors of the study also highlight that although its portion among all greenhouse gases 'concentration in the atmosphere is much smaller than carbon-dioxide (methane being only 16%), methane, by itself, stands as a more severe threat to the environment by being a more potent gas for boosting global warming and climate change problems. The study highlights coal mining activities, natural gas and oil systems, stationary and mobile combustion, and finally, biomass combustion as major sources of methane emission from the energy sector. The result of the study indicates that natural gas and oil production is the largest source of methane emission in the energy sector by 62.22%. Drilling, testing, and servicing of wells (1), production, processing, transmission, storage, and distribution of gas (2), production, upgrading, transport, and refining of oil (3) are also listed as breakdown of specific activities causing methane emission attributed to natural oil and gas production. Secondly, coal mining activities, namely underground mines, surface mines, post-mining operations (processing, transportation, storage of coal mined), and abandoned mines (through unsealed slopes, mine shafts, emission preventive installations), are responsible for approximately one-quarter of the energy sector's methane emission by 24.13%. Finally, nearly 13.65% of the methane emission from energy sector is attributed to combustion-related activities. More specifically, the study indicates that while biomass combustion causes 10.01%, stationary and mobile combustion activities are responsible for 3.64% of methane emissions in the energy sector. Emission from combustion activities is the result of incomplete combustion processes. In the final section of the study, authors discuss potential methane emission abatement opportunities by highlighting that since 86.35% of methane emission from energy sector is due to oil, natural gas, and coal related activities, focusing on the abatement options within these activities offer more efficient and effective solutions. To sum it up, authors classify relevant mitigation opportunities under 3 major categories: technological upgrades, improvements in operational procedures, and upgraded management practices (Aydin et al., 2012).

In another cross-national analysis, *"Global Warming and the Neglected Greenhouse Gas"*, conducted by Andrew Jorgenson, anthropogenic and social causes of methane emission intensity in the atmosphere are analyzed. Stating methane as the second largest contributor to global warming, Jorgenson tests the effect of country's production of beef and veal, natural gas and oil, biomass energy, economic development, and capital intensity of the country (expressed as GDP per capita), the volume of foreign direct investment to the manufacturing and petroleum sectors, and finally, the level of state environmentalism on the intensity of methane emission. Methane emission intensity is defined as per capita volume of methane in a country expressed in CO_2 equivalent. The author utilizes Ordinary Least Squares (OLS) regression with listwise deletion technique by employing available sample data from all countries. Results of the study revealed that observed increases in country's production of beef and veal, natural gas and oil, and biomass energy have a positively contributive effect to its methane emission intensity. On the other hand, expectedly, study concluded that while the level of government environmentalism has a negative effect on a country's methane emission intensity, increasing volume of foreign direct investment to the manufacturing and petroleum sectors demonstrated a positive effect in country's methane emission intensity (Jorgenson, 1995).

A comprehensive study analyzing different sources of human-driven methane emission by sector was conducted by Rafiu O. Yusuf and his colleagues in 2012. The study confirms findings of previous research and indicates that methane is emitted not only from anthropogenic sources, but also from natural sources such as wetlands, grasslands, lakes, and wildfires. Employing available data from 1990 to 2010 obtained from the US Environmental Protection Agency, the study analyzes possible methane emission sources and groups them under 3 different categories: agriculture, energy, and waste. 20 years' methane emission data depicts that between 1990 and 2010, the volume of methane concentration in the atmosphere increased by 23.5%. Sector-based exploratory analysis of methane emission data concluded that all three sectors experienced a significant increase in their volume of methane leaked to the atmosphere by 24%, 32%, and 12% respectively. Study results also provide identical outcomes as similar examples from available literature in this field. Study results show that the largest proportion of the anthropogenic methane emission is attributed to the agriculture sector by 52.5%. Breakdown analysis of agriculture sector's components indicates that enteric fermentation has the highest contribution to the human-driven methane emission by 53% of the whole methane emitted from agricultural activities. Manure management and rice cultivation are responsible for 11% and 18% respectively. The rest of the emissions in the agricultural sector (18%) are attributed to other sources. The energy sector is second to agriculture in terms of global anthropogenic methane emission with its portion of 28% of total. Breakdown of methane emission from energy sector uncovers that activities from oil and gas operations, coal mining, stationary and mobile sources, and biomass conversion are main drivers of the methane leakage in this sector. Emission from oil and gas activities, coal mining activities, biomass conversion, and stationary and mobile sources is found to constitute 18%, 6%, 3%, and 1% of global anthropogenic methane emission. Finally, the waste sector is noted as the third largest sector in terms of contributing to human-made methane emission globally. Constituting 19% of the global, methane emission from waste sector is mainly attributed to solid waste landfill and wastewater treatment activities whose shares in total anthropogenic methane emission are 10% and 8% respectively. Finally, the study also provides numerous practices to deal with the increasing methane emission by presenting various mitigation strategies (Yusuf et al., 2012).

A recent study by Chai Xioali and his colleagues in 2016 which discusses major activities that result in anthropogenic methane emission and provides forecasted figures by employing numerous enhanced estimation models. This study also identifies identical activities that play role as causing highest proportion of human-driven emission of the greenhouse gas. However, rather than categorizing these activities under numerous groups, the authors discuss 5 specific segments that result in 68% of anthropogenic methane emission. These segments are listed as agriculture, oil and gas operations, coal, landfills, and wastewater. The paper starts by discussing actual negative externalities caused by methane and its potential to damage climate in terms of its significantly higher warming capacity. Next, the authors describe major anthropogenic activities causing emission of greenhouse gases. Activities related to agricultural sphere, coal mines, landfills, oil and gas operations, and wastewaters are discussed comprehensively. The study continues by analyzing landfill operations further in the example of USA and China which are known to be two of the largest economies. In the following section, emission estimation models from various institutions are discussed such as LandGEM model of United States Environmental Protection Agency or IPCC model of the United Nations. Finally, the study concludes by identifying various techniques to utilize methane as an energy reservoir and offering various emission mitigation strategies by employing technological advancements and support from government (Xiaoli et al., 2016).

A study published in 2016, *"Attributing Atmospheric Methane to Anthropogenic Emission Sources"*, classifies methane emission sources under 3 categories (biogenic, geonic, and anthropogenic) and elaborate on the specific human-related activities that results in the highest emission of the greenhouse gas such as natural gas and petroleum systems, enteric fermentation (livestock), landfills, coal mining, and manure management as supported by the United States Environmental Protection Agency. On the other hand, biogenic and geonic categories of emission are attributed to the activities from wetlands, termites, and hydrates. Although various natural or anthropogenic sources of the methane emission are known, the current study argues that there is no viable number of studies analyzing relative magnitude of the methane emission attributed to specific sources. With the purpose of removing uncertainty about the emission measurements, the paper discusses and compares several methods such as "bottom-up" and "top-down" to attribute atmospheric methane to emission sources though none of them provides sufficiently satisfactory results because of missing or unreported emission figures (Allen, 2016).

A study conducted by Scott Miller et al., attempts to quantify atmospheric methane emission estimates in the United States which are attributed to human-related activities. Due to the discrepancy among reported figures from various sources and measurement techniques (e.g. bottom-up and top-down approach), in this study, various emission measurement techniques, comprehensive emission observations at the surface, on telecommunications towers, and from aircraft, combined with an atmospheric transport model, a geostatistical inverse modeling (GIM) framework, auxiliary spatial data (e.g., on population density and economic activity), and leverage concurrent measurements of alkanes have been employed to estimate the actual or relatively more accurate volume of emission of methane in United States by sector. In order to provide effective government regulation over greenhouse gas emissions, accuracy of the reported numbers is highly crucial; therefore, this study provides insightful results for more efficient and effective administration and governing procedures. Results of the examination conclude that anthropogenic methane emission in the United States is mainly attributed to two major sources: fossil fuel extraction and animal husbandry. Similar to the previously conducted studies, the study results also reveal that operations related to natural gas and oil industry (processing, refining, storing, and etc.) result in the emission of greenhouse gas. Similarly, activities regarding animal husbandry such as livestock and manure management are among significant emission sources for methane attributed to anthropogenic activities. In addition to that, examination results also revealed that actual volume of greenhouse gas emission is, indeed, much higher than the figures reported by the official sources such as US Environmental Protection Agency (EPA) and the Emissions Database for Global Atmospheric Research by factors of 1.5 and 1.7 respectively (Miller et al., 2013).

In another report, published in 2018, Alvarez and his colleagues assess the emission of methane in the United States by focusing on the country's oil and natural gas supply chain. Similar to the various literature materials, by employing top-down and bottom-up measurement techniques, this study provides assessment of methane emission in natural gas and oil sector related activities. The assessment provides two main results. Firstly, activities in the oil and natural gas sector cause a significant amount of methane emission as a result of industry related operations such as processing, refinery, transportation, and storage. Secondly, emission of methane from oil and natural gas sector is significantly higher than the emission figures provided by Environmental Protection Agency (EPA). Authors of the study link this discrepancy in the emission figures to the fact that sampling methods and practices employed by EPA do not consider malfunctional and abnormal operating processes such as leaks from equipment and pneumatic controllers. Finally, highlighting feasibility of significant emission-mitigation opportunities, the study also provides methane emission reduction techniques for oil and natural gas sectors such as deployment of effective emission detection systems as well as repair systems (Alvarez et al., 2018).

Another study analyzing anthropogenic sources of methane emission has been conducted by Hoglund Isaksson. The study, named "*Global anthropogenic methane emissions 2005–2030: technical mitigation potentials and costs"*, identifies major sources, presents estimates regarding methane emission figures, and provides technical mitigation opportunities associated with their calculated costs. Uncovering global sources of human-driven methane emission, the study identifies 40 sources of greenhouse gas emission. Agricultural husbandry, cereal production, biodegradable solid waste, wastewater, coal mining activities, oil and gas production, gas transmission pipelines, gas distribution networks, fuel combustion, and waste combustion are listed as major sources of emission attributed to human activities. By using methane emission data of 83 countries, the study estimates methane emission by employing GAINS model framework for 2005-2030 timeframe and provides methane emission mitigation strategies grouped under 11 categories. Finally, following probable cost savings as a result of emission mitigation, based on GAINS model framework, the author also presents emission mitigation cost calculation results which include investment, labor, operation, and maintenance costs associated with the mitigation practices (Isaksson, 2012).

In another recently published article, Jackson et al., investigate the main causes of increasing volume of global methane emission in the atmosphere and attempt to compare estimated methane emission figures to the average values of the reference period, 2000-2006. As several examples of available literature, the current study also employs top-down and bottom-up approaches for obtaining global methane emission estimate from various sources. Results of the top-down analysis conclude that 61% of total methane emission was due to human-related activities in 2017. On the other hand, bottom-up approach results indicated the portion of anthropogenic methane emission as 51%. The observed increase in the volume of methane emission for the estimated and reference period is found to be mainly due to the emissions from anthropogenic activities. While the top-down approach associated increasing methane emission volume to fossil fuel extraction by 40% and agriculture, together with waste activities, by 60%. On the other hand, the bottom-up approach of estimating methane emission associated the estimated increase in the greenhouse gas emission to fossil fuel extraction by 56% and agriculture, together with waste activities, by 44%. Although based on the results of the study, different approaches provide slightly different estimates regarding emission figures specific to each sector, both methods confirm findings of available studies that increase in the methane emission figures is due to the anthropogenic activities (e.g. enteric fermentation, manure management, landfills and waste, rice cultivation, coal mining, oil and gas production, and biomass and biofuel combustion). Finally, the study also concludes that while United States and southern and southeastern Asia experience increasing anthropogenic methane emission volume, a decreasing volume of the emission is observed in Europe (Jackson et al., 2020).

As various examples from academic literature are provided in this section, dependent and independent variables of the study must be introduced. Throughout this paper, dependent and independent variables are recalled as response and explanatory variables respectively. Methane emission from energy sector will be used as dependent variable of the study. *Total oil and natural gas production, natural gas flaring, coal consumption,* and *hydroelectricity generation* will be used as independent or explanatory variables. More detailed information about response and explanatory variables will be presented in the *data and methodology* section of this paper. In the conceptual framework presented below (Exhibit 1), the relationship between independent variables (IV) and dependent variable (DV) is illustrated graphically:

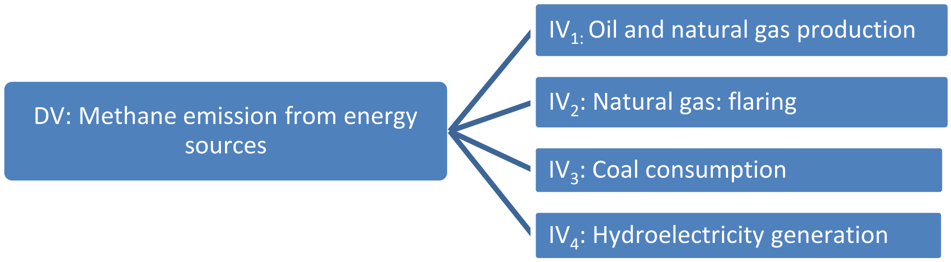


Exhibit 1: Conceptual Framework

All in all, to conclude the literature review section of this current study, based on the various examples from academic literature, hypotheses of this study can be constructed as follows which are going to be tested throughout the paper:

- *Hypothesis 1: Oil and natural gas production has a positive effect on methane emission from energy sector.*
- *Hypothesis 2: Flaring from natural gas has a positive effect on methane emission from energy sector.*
- *Hypothesis 3: Coal consumption has a positive effect on methane emission from energy sector.*
- *Hypothesis 4: Hydroelectricity generation has a positive effect on methane emission from energy sector.*

To clarify any possible confusion regarding interpretation of the above-given hypothesis, in the context of this paper, "*positive effect*" means a contribution that increases the emission volume of methane from energy sector. On the other hand, "*negative effect*" means a contribution that decreases the emission volume of methane from the energy sector.

The last element of the listed hypotheses which also performs as one of the independent variables of the study is *hydropower* or *hydroelectricity generator* from hydro sources. While electricity generated from hydropower constitutes an important source of energy, recent studies conclude that hydropower plants constitute serious impact towards climate and its effect is often stated to be more significant than the impact of coal, oil, natural gas, and other fossil fuel extraction activities (Nature, 2006). Therefore, inclusion of this variable in the current study is thought to provide valuable insights.

More detailed information about variables of the study, such as units of measurement and selected time-period, is presented in the following *Data and Methodology* section.

Data and Methodology

The Data and Methodology section presents data collection and data analysis methods and provides more comprehensive information about the response and explanatory variables of the study.

Study variables. *Methane emission from energy sources* is used as dependent or response variable while *natural gas and oil production, coal consumption,* and *hydroelectricity generation* are determined as independent or explanatory variables of the study. 30 years' historical data for the selected variables are obtained from official sources. More detailed information about each variable's unit of measurement and the obtained data source is provided below:

- *Methane emission from energy sources*, dependent variable of the study, is expressed in thousand metric tons of CO_2 equivalent and the data is obtained from The World Bank (2023). It includes the volume of annual methane emitted as a result of activities from energy market.
- *Natural gas and oil production,* the first independent variable of the study, refers to the annual volume of production expressed in *tons*. The data is obtained from *Annual Statistical Review of World Energy* report published by British Petroleum. The report presents oil production itself in *million tons* and calculation includes crude oil, shale oil, oil sands, condensates (lease condensate or gas condensates that require further refining) and NGLs (natural gas liquids - ethane, LPG and naphtha separated from the production of natural gas), and excludes liquid fuels (from other sources such as biofuels and synthetic derivatives of coal and natural gas), liquid fuel adjustment factors (such as refinery processing gain), and oil shales/kerogen extracted in solid form. On the other hand, natural gas production is presented in *billion cubic meters* and calculation excludes flared or recycled gas, but includes natural gas produced for gas-to-liquids transformation (BP, 2023). Data analysis results demonstrate that strong correlation figures exist between natural gas and oil production variables for all three countries, Azerbaijan, Kazakhstan, and Russia by 85%, 99%, and 81% respectively (Appendix 1). Therefore, in order to obtain valid test results by avoiding strong internal correlation among independent variables, which is going to be elaborated further in following parts of the section,

for the sake of analysis, natural gas and oil production figures are summed up and included to the research as a single variable, *natural gas and oil production.* So, natural gas figures are converted to *tons* by multiplying *billion cubic meter* values by 678,000 (Hebrew Energy, 2023). *Natural gas production* numbers calculated by *tons* are, then, summed up with the *oil production* numbers which are expressed in *tons* as well.

- *Flaring from natural gas* represents second independent variable of the study and expressed in *billion cubic meters* (BP, 2023).
- The third independent variable of the study is *coal consumption* which refers to the annual volume of coal consumption expressed in *exajoules*. The numbers are also obtained from *Annual Statistical Review of World Energy* report published by British Petroleum and excludes coal converted to liquid or gaseous fuels, but includes coal consumed in transformation processes (BP, 2023).
- The last independent variable is *hydroelectricity generation* expressed in *terawatt-hours* and includes gross primary hydroelectric generation and not accounting for cross-border electricity supply (BP, 2023).

Data Collection. Within the scope of this study, two main data collection methods are used. Firstly, *secondary data* is gathered from official sources for statistical analysis and visualization of the historical data for selected variables. As described in the earlier paragraphs, officially reported data regarding the variables of the study is obtained from sources as *The World Bank* and *British Petroleum*.

Primary data collection method is employed to gather original data regarding methane emission and its specifics associated with Azerbaijan. As a tool to collect original data, semi-structured interviews are held with the experts of the field. A semi-structured type of interview is a data collection technique by which interviewer asks questions to the respondent or interviewee in a predetermined order and the interview process might include any prompt questions from the interviewer. Overall, three interviews were held with the experts from the field of ecology, environment, health, and safety in an online format. More background information about the interviewees and interviews are included in the appendix along with the interview questions (Appendix 2).

Exploratory Data Analysis (EDA). With the purpose of acquiring better understanding of datasets, identifying patterns, detecting outliers, summarize key descriptive statistics, and testing research hypotheses, *exploratory data analysis* is a widely-used data analysis technique (IBM, 2023) which is employed in this study as well. Output of the exploratory data analysis provides certain descriptive statistics as number of observations, mean, standard deviation, minimum, and maximum values for each variable. Moreover, correlation matrix is used to provide correlation coefficients for independent variables of the study which will also be elaborated in the following paragraphs. Additionally, various types of charts (e.g. line graphs and histograms) are used for providing a better understanding and description of the numbers through visualization.

Multiple Linear Regression (MLR). Regression model is used to estimate the relationship between an explanatory and a response variable. When a relationship between multiple independent (at least two) and a single dependent variable is tested, multiple linear regression is used which is the identical case for this study (one dependent variable and 4 independent variables). While the result of the multiple linear regression provides several important points, three major insights are usually obtained as a result of MLR analysis (Peck et al., 2005):

- *The direction of the relationship between dependent and independent variables.*
- *The strength of the relationship between dependent and independent variables.*
- *How a dependent variable changes in relation to a change in the independent variable.*

Output of the MLR analysis provides a regression equation in which effects of 4 independent variables on the dependent variable are illustrated:

$$Y_i=\beta_0+\beta_1x_1+\beta_2x_2+\beta_3x_3+\beta_4x_4+\epsilon$$

- *Y: dependent variable of the model*
- *B_0: intercept value*
- *B_1: coefficient of the first independent variable of the model*
- *B_2: coefficient of the second independent variable of the model*
- *B_3: coefficient of the third independent variable of the model*

- *B_4: coefficient of the fourth independent variable of the model*
- *x_i: value of the independent variable*
- *ϵ: error term*

There are four main assumptions to meet in Multiple Linear Regression Analysis (Peck et al., 2005):

1. *Homoscedasticity*: the assumption of homogeneity of the variances in the model is tested through *White test* or *Breusch–Pagan test* (Appendix 8).
2. *No multi-collinearity*: absence of correlation among independent variables. The second assumption of the Multiple Linear Regression, *absence of multi-collinearity*, is tested by two methods. The first method is using *correlation matrix* to detect correlation coefficients among independent variables. The existence of high correlation coefficients recalls the existence of multi-collinearity. The second method of detecting multi-collinearity is employing *Variance Inflation Factor* (VIF) method. VIF value which is not greater than 10 usually indicates absence of the multi-collinearity and vice-versa.
3. *Normality*: the assumption satisfies that variables are normally distributed. Normality assumption is checked by employing *histograms* or using *skewness tests* in Stata software.
4. *Linearity*: the assumption satisfies a linear relationship between dependent and independent variables. By using *two-way scatter plot* or *fit plots*, linearity assumption of MLR is tested in Stata software.

To sum up the *data and methodology* section, in this study, one dependent variable (*methane emission from energy sector)* is tested against four independent variables (*natural gas and oil production, flaring from natural gas, coal consumption*, *and hydroelectricity generation).* Gathering data through both primary and secondary data collection methods, *exploratory data analysis* and *multiple linear regression analysis* are to be presented. The outcome of the mentioned analysis is presented in the *Results and Findings* section of this paper.

Results and Findings

In this section of the paper, results of the analysis and interviews, highlighted in the *data and methodology* section, are elaborated and further discussions regarding those results are provided.

Exploratory Data Analysis (EDA). To start with the *EDA* results, by employing Stata software, descriptive statistics respective to each country regarding each variable is illustrated below.

Table 1: Descriptive statistics for Azerbaijan

Variable	Obs	Mean	Std. Dev.	Min	Max
methanefro~y	30	5775	3202.52	2020	14020
TotalOilan~n	30	3.42e+07	1.94e+07	1.27e+07	6.23e+07
Coalconsum~J	30	.0003318	.0008122	0	.0037263
Naturalgas~b	30	4.321827	3.784641	.1813243	12.5775
Hydroelect~H	30	1.986743	.5259815	1.2997	3.4463

Table 2: Descriptive statistics for Kazakhstan

Variable	Obs	Mean	Std. Dev.	Min	Max
methanefro~y	30	21172	7420.807	10420	30130
TotalOilan~n	30	6.72e+07	3.35e+07	2.25e+07	1.14e+08
Naturalgas~g	30	1.720615	1.084442	.2925	3.840338
Coalconsum~J	30	1.29473	.2876462	.7468706	1.704784
Hydroelect~H	30	8.133255	1.327123	6.132	11.62076

Table 3: Descriptive statistics for Russia

Variable	Obs	Mean	Std. Dev.	Min	Max
methanefro~y	30	423915	43423.34	349830	517750
TotalOilan~n	30	8.43e+08	1.18e+08	6.62e+08	1.03e+09
Hydroelect~H	30	170.9491	9.966953	154.309	194.3761
Coalconsum~J	30	4.483992	1.02775	3.513981	7.632768

As summary table output illustrates, 30 observations for each of the included variables, both dependent and independent, are available in the obtained dataset for all the selected countries for the observed 30 years' time period, 1990-2019. Based on these observation figures, mean, standard deviation, minimum, and maximum values of the observations are demonstrated specific to each variable. An exception regarding independent variables of Russia should be highlighted that due to the unavailability of the *natural gas flaring* data for Russia, the table of descriptive statistics does not include information regarding that variable specifically. It also leads to a conclusion that in analyzing the relationship between dependent and independent variables, *flaring from natural gas* is not included to the MLR analysis for Russia.

A detailed look at the summary tables of descriptive statistics reveals that in comparison of maximum values observed for each variable, Russia dominates among these countries excepting the variable of *natural gas flaring*. While the data is unavailable for Russia, Azerbaijan demonstrates a higher indicator of maximum *natural gas flaring* value in comparison with Kazakhstan. On the other hand, Azerbaijan also demonstrates lowest minimum values for every variable among all three countries with the exception of *natural gas flaring variable*.

In addition to the summary statistics, correlation matrixes also provide insightful results regarding the direction and strength of the relationship among independent variables. In the book, *"The basic practice of statistics"*, Moore and colleagues note that an absolute value of the correlation coefficient greater than 0.7 indicates a strong relationship between two variables (2013). However, it should be considered that in this paper, VIF method is used to conclude if the strength of the relationship between two variables is so strong that it fails to satisfy MLR assumption of *absence of multi-collinearity*.

Table 4: Correlation matrix for independent variables: Azerbaijan

	TotalO~n	Coalco~J	Natura~b	Hydroe~H
TotalOilan~n	1.0000			
Coalconsum~J	-0.2137	1.0000		
Naturalgas~b	-0.8456	0.5791	1.0000	
Hydroelect~H	0.1904	-0.1177	-0.2304	1.0000

Table 4 provides correlation coefficients for independent variables observed in the case of Azerbaijan. With a value of *-0.85*, a strong negative relationship is depicted between *oil and natural gas production* and *flaring of natural gas*. No other significantly strong relationship is observed among independent variables for data of Azerbaijan.

Table 5: Correlation matrix for independent variables: Kazakhstan

	TotalO~n	Natura~g	Coalco~J	Hydroe~H
TotalOilan~n	1.0000			
Naturalgas~g	0.8170	1.0000		
Coalconsum~J	0.5088	0.3901	1.0000	
Hydroelect~H	0.5435	0.2710	0.4029	1.0000

Table 5 also highlights a strong, yet positive, relationship for *oil and natural gas production* and *flaring of natural gas* in Kazakhstan with a value of *0.82*.

Table 6: Correlation matrix for independent variables: Russia

	TotalO~n	Hydroe~H	Coalco~J
TotalOilan~n	1.0000		
Hydroelect~H	0.5807	1.0000	
Coalconsum~J	-0.3110	-0.2398	1.0000

Finally, according to *Table 6*, no significantly strong relationship among independent variables of Russia is observed.

Additionally, graphical illustration of historical figures by *line graphs*, distribution of values by frequency by *histograms*, and *boxplots* for detection of outliers for all the variables respective to each of three countries are demonstrated in the Appendix 3, Appendix 4, and Appendix 5 respectively.

Multiple Linear Regression Analysis results. As it is stated in the *data and methodology* section of the paper, in order to test the assumption of multi-collinearity in regression model, Variance Inflation Factor (VIF) method is used. As a result, none of the selected countries demonstrated a VIF value higher than 10. Thus, it enables us to conclude that the assumption of no-multi-collinearity is satisfied in the regression model. More detailed and comprehensive information regarding variance inflation factors attributed to each country specifically is also presented in Appendix 7.

Results of the regression summary output for Azerbaijan provides detailed information regarding the effects of the independent variables on dependent variable (*Table 7*). Based on the calculated *F statistics,* which is approximately 0.00%, obtained figure indicates that in case of Azerbaijan, constructed regression model is significant. Moreover, R-squared value of 0.8207 interprets that 82.07% of the variation in the *methane emission from energy sector* (dependent variable) is explained by the model. Regarding specific effects of independent variables on the methane emission from energy sector, obtained *p values* conclude that in Azerbaijan, effects of *oil and natural gas production, coal consumption*, and *natural gas flaring* is significant. On the other hand, since p-value associated with the *hydroelectricity generation*, 0.928, is greater than 0.05, the model concludes that *hydroelectricity generation* has no significant effect on *methane emission from energy sector* in Azerbaijan. Obtained coefficient values whose p-value is statistically significant, by being less than 0.05, provide below-given interpretations:

Table 7: Regression summary output: Azerbaijan

Source	SS	df	MS
Model	244099454	4	61024863.5
Residual	53328496	25	2133139.84
Total	297427950	29	10256136.2

Number of obs	= 30
F(4, 25)	= 28.61
Prob > F	= 0.0000
R-squared	= 0.8207
Adj R-squared	= 0.7920
Root MSE	= 1460.5

methanefromenergy	Coef.	Std. Err.	t	P>|t|	[95% Conf.	Interval]
TotalOilandGasproductionton	.000178	.0000339	5.25	0.000	.0001082	.0002477
CoalconsumptionEJ	2011605	530040.9	3.80	0.001	919965.1	3103244
Naturalgasflaringbillioncub	618.9579	209.2999	2.96	0.007	187.8967	1050.019
HydroelectricitygenerationTwH	48.69938	530.1941	0.09	0.928	-1043.256	1140.655
_cons	-3756.962	2243.846	-1.67	0.107	-8378.25	864.3256

- A unit increase in *total oil and natural gas production* is estimated to result in an increase of 0.000178-unit in *methane emission from energy sector*. In other words, increasing the production of oil and natural gas by one thousand tons is estimated to increase methane emission from energy sector by 0.178 thousand metric tons of CO_2 equivalent.
- A unit increase in *coal consumption* is estimated to result in 2,011,605-unit increase in the volume of *methane emission from energy sector*. In other words, increasing the consumption of coal by one exajoules is estimated to increase methane emission from energy sector by 2,011,605 thousand metric tons of CO_2 equivalent.

- A unit increase in *natural gas flaring* is estimated to result in an increase of 618.9579-unit in the volume of *methane emission from energy sector*. In other words, a billion cubic meters increase in natural gas flaring is estimated to increase methane emission from energy sector by 618.9579 thousand metric tons of CO_2 equivalent.
- *Hydroelectricity generation* indicated no statistically significant relationship with a coefficient value of 48.69938. Since this variable indicates positive effect in methane emission in the example of two other countries (will be provided in further paragraphs) and earlier studies, this result was unexpected. A possible explanation for insignificant effect of hydroelectricity generation in methane emission in Azerbaijan is estimated to be due to the comparably small volume of the variable in Azerbaijan in comparison to Kazakhstan and Russia (Appendix 6).

So, in case of Azerbaijan, results of the regression output can be summarized in below-given regression equation:

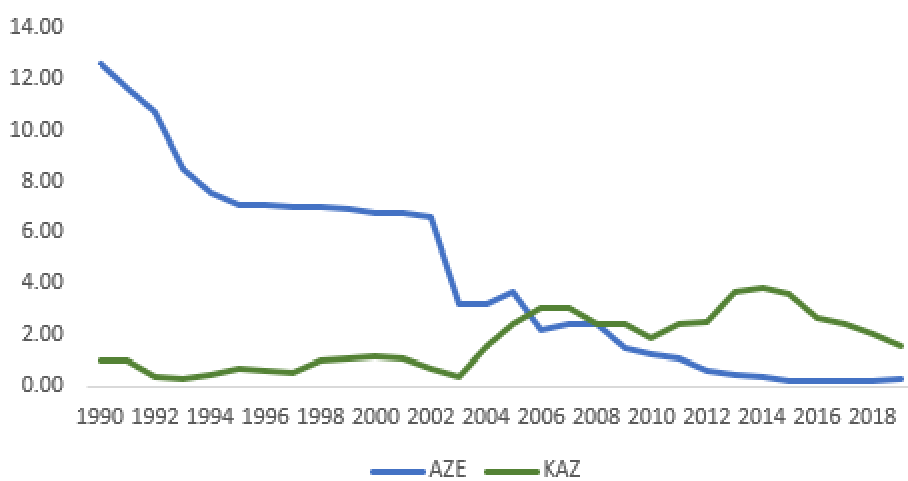
$$\textit{Methane Emission} = -3756.962 + 0.000178(X_1) + 2011605(X_2) + 618.9579(X_3) + 48.7(X_4) + \epsilon$$

Regression results provide following conclusions regarding hypotheses of the study attributed to Azerbaijan:

- *Hypothesis 1: Oil and natural gas production has a positive effect on methane emission from energy sector.*
- *Hypothesis 2: Coal consumption has a positive effect on methane emission from energy sector.*
- *Hypothesis 3: Flaring from natural gas has a positive effect on methane emission from energy sector.*
- *Hypothesis 4: Hydroelectricity generation has no effect on methane emission from energy sector.*

Secondly, results of the regression summary output for Kazakhstan provides detailed information regarding the effects of the independent variables on dependent variable (*Table 8*). Based on the calculated *F statistics,* which is approximately 0.00%, obtained figure indicates that in case of Kazakhstan, constructed regression model is significant. Moreover, R-squared value of 0.9683 interprets that 96.83% of the variation in the methane emission from energy sector (dependent variable) is explained by the independent variables of the study. Regarding specific effects of independent variables on the methane emission from energy sector, obtained *p values* indicate that in Kazakhstan, effects of *oil and natural gas production, coal consumption*, and *hydroelectricity generation* is significant. On the other hand, since p-value associated with the *natural gas flaring*, 0.197, is greater than 0.05, the model concludes that *natural gas flaring* has no significant effect on *methane emission from energy sector* in Kazakhstan. Comparing natural gas flaring figures of Azerbaijan and Kazakhstan provides a possible explanation why natural gas flaring demonstrated insignificant effect on the volume of methane emission for Kazakhstan. Visualizing *natural gas flaring* data for two countries for the period of 1990-2019, below given graph indicates that over the past 30 years', Kazakhstan's natural gas flaring volume has been significantly lower than Azerbaijan until 2006 since when the gap between two countries' became smaller. Significantly lower volume of natural gas flaring in Kazakhstan compared to Azerbaijan's provides a reasonable explanation why this variable indicated insignificant effect on methane emission as a result of regression analysis (Appendix 3).

Graph 1: Natural gas flaring (billion cubic meters): Azerbaijan and Kazakhstan



Obtained coefficient values whose p-value is statistically significant, by being less than 0.05, provide below-given interpretations:

Table 8: Regression summary output: Kazakhstan

Source	SS	df	MS
Model	1.5463e+09	4	386573152
Residual	50690272.3	25	2027610.89
Total	1.5970e+09	29	55068375.2

Number of obs	30
F(4, 25)	190.65
Prob > F	0.0000
R-squared	0.9683
Adj R-squared	0.9632
Root MSE	1423.9

methanefromenergy	Coef.	Std. Err.	t	P>|t|	[95% Conf.	Interval]
TotalOilandGasproductionton	.0002302	.0000172	13.37	0.000	.0001948	.0002657
Naturalgasflaring	600.5673	452.8157	1.33	0.197	-332.024	1533.159
CoalconsumptionEJ	-4454.709	1084.587	-4.11	0.000	-6688.458	-2220.959
HydroelectricitygenerationTwH	-619.6632	257.8132	-2.40	0.024	-1150.639	-88.68699
_cons	15486.79	1960.039	7.90	0.000	11450.02	19523.57

- A unit increase in *oil and natural gas production* is estimated to result in an increase of 0.0002302-unit in *methane emission from energy sector*. In other words, increasing the production of oil and natural gas by one thousand tons is estimated to increase methane emission from energy sector by 0.2302 thousand metric tons of CO_2 equivalent.
- A unit increase in *coal consumption* is estimated to result in 4454.709-unit decrease in the volume of methane emission from energy sector. In other words, increasing the consumption of coal by one exajoules is estimated to decrease methane emission from energy sector by 4454.709 thousand metric tons of CO_2 equivalent.
- A unit increase in *hydroelectricity generation* is estimated to result in a decrease of 619.6632-units in the volume of methane emission from the energy sector. In other words, a terawatt hour increase in hydroelectricity generation is estimated to decrease methane emission from energy sector by 619.6632 thousand metric tons of CO_2 equivalent.
- *Natural gas flaring* indicated no statistically significant relationship with a coefficient value of 600.5673.

In case of Kazakhstan, results of the regression output can be summarized in below-given regression equation:

$$\textbf{\textit{Methane Emission}} = 15486.79 + 0.0002302(X_1) + 600.5673(X_2) - 4454.709(X_3) - 619.6632(X_4) + \epsilon$$

Regression results provide following conclusions regarding hypotheses of the study attributed to Kazakhstan:

- *Hypothesis 1: Oil and natural gas production has a positive effect on methane emission from energy sector.*
- *Hypothesis 2: Flaring from natural gas has no statistically significant effect on methane emission from energy sector.*
- *Hypothesis 3: Coal consumption has a negative effect on methane emission from energy sector.*
- *Hypothesis 4: Hydroelectricity generation has a negative effect on methane emission from the energy sector.*

Finally, results of the regression summary output for Russia provides detailed information regarding the effects of the independent variables on dependent variable (*Table 9*). Based on the calculated *F statistics,* which is approximately 0.00%, obtained figure indicates that in case of Russia, constructed regression model is significant. Moreover, R-squared value of 0.9711 interprets that 97.11% of the variation in the methane emission from energy sector (dependent variable) is explained by the current model. Regarding specific effects of independent variables on the methane emission from energy sector, obtained *p values* indicate that in Russia, effects of all three variables tested, *total oil and natural gas production, coal consumption*, and *hydroelectricity generation* are significant. On the other hand, since natural gas flaring is not available for Russia, effect of this variable on methane emission from energy sector is not tested in the regression model of Russia. Obtained coefficient values provide below-given interpretations:

Table 9: Regression summary output: Russia

Source	SS	df	MS
Model	5.3102e+10	3	1.7701e+10
Residual	1.5804e+09	26	60784837.2
Total	5.4682e+10	29	1.8856e+09

Number of obs =	30
F(3, 26) =	291.20
Prob > F =	0.0000
R-squared =	0.9711
Adj R-squared =	0.9678
Root MSE =	7796.5

methanefromenergy	Coef.	Std. Err.	t	P>|t|	[95% Conf.	Interval]
TotalOilandGasproductionton	.0003422	.0000155	22.14	0.000	.0003104	.0003739
HydroelectricitygenerationTwH	586.662	178.9537	3.28	0.003	218.8174	954.5065
CoalconsumptionEJ	4329.411	1486.553	2.91	0.007	1273.756	7385.065
_cons	15795.96	27995.12	0.56	0.577	-41748.84	73340.75

- A unit increase in *oil and natural gas production* is estimated to result in an increase of 0.0003422-unit in *methane emission from the energy sector*. In other words, increasing the production of oil and natural gas by one thousand tons is estimated to increase methane emission from energy sector by 0.3422 thousand metric tons of CO_2 equivalent.
- A unit increase in *hydroelectricity generation* is estimated to result in an increase of 586.662-unit in the volume of *methane emission from energy sector*. In other words, a terawatt hour increase in hydroelectricity generation is estimated to increase methane emission from energy sector by 586.662 thousand metric tons of CO_2 equivalent.
- A unit increase in *coal consumption* is estimated to result in 4329.411-unit increase in the volume of *methane emission from energy sector*. In other words, increasing the consumption of coal by one exajoules is estimated to increase methane emission from energy sector by 4329.411 thousand metric tons of CO_2 equivalent.

So, in case of Russia, results of the regression output can be summarized in below-given regression equation:

$$\textit{Methane Emission} = 15795.96 + 0.0003422(X_1) + 586.662(X_2) + 4329.411(X_3) + \epsilon$$

Regression results provide following conclusions regarding hypotheses of the study attributed to Russia:

- *Hypothesis 1: Oil and natural gas production has a positive effect on methane emission from energy sector.*
- *Hypothesis 2: Coal consumption has a positive effect on methane emission from energy sector.*
- *Hypothesis 3: Hydroelectricity generation has a positive effect on methane emission from the energy sector.*

Interviews' results. As stated in the *data and methodology* section, gathering primary data from experts of the field through semi-structured interviews is important in terms of obtaining comprehensive and versatile responses from individuals with actual industrial field experience. Interview questions and further details are described in Appendix 2. In the following paragraphs, the main takeaways from interviewees are described.

The first interview with a high-level administrative representative of "Təmiz Şəhər" OJSC clarified specific points regarding methane emission. The company operates in the solid waste management industry and aims to improve country-wide ecological conditions by implementing its daily activities according to up-to-date standards. During the interview process, respondent elaborated on specific points regarding methane emission in Azerbaijan:

"First of all, it is mentioned that along with the activities from oil and gas operations and agricultural field, in Azerbaijan, significant volume of methane is emitted from waste sector through landfills. Decomposition of waste materials in landfills is said to result in the emission of CH_4 through 5 step-process:

1. Oxidization process during initial collection of waste materials in waste collection points.
2. Emergence of liquids from waste materials which starts the initial emissions of greenhouse gases.
3. Actual emission of greenhouse gas emissions: the respondent highlighted that the majority of the methane emission happens in this stage of decomposition process.
4. Emission from landfills is detected, caught, and stored through technical generative machines which later, turns into electricity energy (approximately 2-megawatt power) to be used in the industry as energy source.
5. The final stage of decomposition is where the emission process is terminated.

Additional information by the respondent also revealed that from ecological perspective, instead of focusing on achieving concrete elimination of methane emission, accomplishing the balance of methane in atmosphere should be the main goal since emission of methane also contains certain benefits as a source of energy.

In its commercial operations, to achieve a reduction in the emission of methane and benefit from its various uses as a source of energy, "Təmiz Şəhər" OJSC performs as a member of numerous international conventions. By highlighting the fact that landfills under the management of institution is provided with high-level technological tools and mechanism, respondent concluded that in terms of waste management activities, Azerbaijan is not behind the practice of other developed countries. A specific recommendation from the expert was highlighted regarding improving literacy of the population about methane emission, its sources, potential threats, and benefits provided by CH_4.

Finally, it was also noted that while achieving reduction in the emission of methane is a crucial mission, focusing on the reduction from anthropogenic sources should be the main scope of emission mitigation strategies instead of pursuing reduction from natural sources" (Aliyev, 2023).

The second interview was conducted with an ecology expert from the environmental sustainability field with a solid academic background in ecology. Main takeaways from the interview are presented below:

"The interviewee confirmed that according to the official sources (e.g. UNEP), methane is accepted as a potentially harmful gas causing greenhouse effect in the atmosphere which eventually results in climate problems. Fossil fuel extraction, agricultural activities, incomplete combustion, fuel production and refinery are listed as main activities causing methane emission in Azerbaijan.

The expert noted that in comparison with government-level actions toward carbon-dioxide reduction, actions for mitigation of methane emission are not necessarily less concentrated. Especially in the oil and gas industry, adaptation of modern technologies and regulating industry standards have turned out to be an important focus.

Regarding administrative actions to cease greenhouse gas emission, the respondent exemplifies a recent *Presidential Decree* which exempted custom fees for import of modern machinery in oil and gas industry. Implementation of modern technology is expected to mitigate CH_4 emission.

Finally, the expert believes that although methane emission has no observed and reported direct influence on human health, through indirect means of greenhouse effect and ultraviolet rays, it stands as a potential threat to health of living species" (Abdullayev, 2023).

The third and final interview within this study was conducted with an HSE (health, safety, environment) expert from a local private company. The interview uncovered various captivating points regarding methane emission in Azerbaijan:

> "The expert noted that although specific emission volume is not currently available, emitting to the atmosphere as a result of processes of oil extraction, processing, transportation, and storage, methane posits as a potentially harmful greenhouse gas to the environment. Additional sources of emission, such as enteric fermentation and manure management, were noted as well.
>
> By referring to an external source, respondent drew attention to the increase of emission volume for methane by 3.5% since 1990 (UNFCC, 2023). Considering the negative effect of CH_4 emission to the climate, expert notes that in Azerbaijan, specific mitigation actions are taken by SOCAR and BP towards methane emission; however, data regarding the effect of those measures are not currently available.
>
> As noted in *Fourth National Communication Plan to the United Nations Framework Convention on Climate Change* prepared by the Ministry of Ecology and Natural Resources Republic of Azerbaijan, currently, specific greenhouse gas emission mitigation plans are being implemented in various fields of the economy of Azerbaijan such as oil and gas, agriculture, and waste management (2021). Finally, expert also confirmed negative effects of methane emission to human health" (2023).

To sum up the main takeaways from the conducted interviews, experts maintain the consensus that methane emission is mainly caused by natural gas and oil production, agricultural activities such as enteric fermentation, animal husbandry, manure management, and waste management activities. Moreover, ongoing administrative actions toward mitigation of the greenhouse gas emissions have also been highlighted in the interviews. So, despite constituting potential benefit as a source of renewable energy, according to experts, methane emissions are noted to be managed effectively in order to minimize its environmentally hazardous effects.

Recommendations

As comprehensively elaborated in the previous paragraphs of this study, mitigation of methane emission plays a crucial role in preventing global warming and achieving global climate goals. In order to achieve the established goals to prevent and control climate change, limiting methane leakage from oil and gas industry is among the most cost-effective policies to be taken by the government. Considering the negative impact of emission of methane in global warming, national level actions from governments are also encouraged along with voluntary actions of the industries (IEA, 2023). In this section of the paper, as a result of the interviews conducted with the experts of the field, mitigation strategies and opportunities for methane emission from energy sources, mainly from oil and natural gas sectors, are presented and discussed. During the interviews, experts brought up insightful strategies and technical solutions derived from the existing field practice and domain knowledge. So, the following paragraphs regarding recommendations for mitigation of methane emission from energy sources contain summarized responses from expert interviews. Overall, these mitigation strategies are grouped into two categories summarized in Table 10.

The first category is related to the *accuracy of the reported emission figures*. Accurate reporting of emission volumes is highlighted to be an important step towards emission mitigation. Following the principle *"you cannot improve what you cannot measure"*, Orbio Earth, global methane emission intelligence agency, stresses the importance of accurate methane emission data in achieving reduction in methane emission volume (2023). However, reported during the interviews, according to the IEA report, systematic monitoring and measurement procedures indicated significant presence of underreporting cases for methane emission volume by official sources. Comparative studies led by IEA revealed that official governmental reports being lower than IEA calculations and there is approximately 70% discrepancy between methane emission figures calculated by IEA and reported by national governments as depicted in Appendix 9 (IEA, 2021). Furthermore, another study published in *Science Journal* highlights that estimated leakage rate in upstream US natural gas production is 2.3% although *Environmental Protection Agency* reported officially estimated leakage rate to be 0.038% (60 times smaller than the actual figure). Possible explanation to the degree of difference between reported and actual leakage rate figures narrates that leakage points emerged as a result of maintenance and equipment failure processes largely contribute to methane emission and since these leakage points stay out of the official reporting scope, official reports, indeed, underestimate the actual methane emission volume (Alvarez et al., 2018). Therefore, implementation of below-given methane emission measurement and reporting strategies is expected to provide more accurate emission figures. Experts recommend below-given technical solutions to mitigate the inaccuracy of the reported emission figures:

- *Implementing satellites for aerial detection and measurement of methane from oil and gas sector.* Analytical results regarding early practices of satellites to measure and estimate the volume of methane emission conclude that they are highly effective and accurate for measuring methane emission from large emission points. Well-performed examples of satellite technology in estimating methane emissions from large leak points are GHGSat-D and TROPOMI (tropospheric monitoring instrument). Experts claim that according to IEA reports, these satellite technologies are proven to provide more accurate methane emission estimates in detecting and measuring greenhouse gas emissions in Canada, mid-western United States, and Central Asia (IEA, 2023).
- *Employing emission detecting sensors*. Methane, being a major element of natural gas, is a colorless odorless, and flammable which makes its detection more challenging (National Library of Medicine, 2023). It was highlighted that locating methane emission detecting sensors on vehicles and equipment in business operations has proven to provide more accurate emission estimates (Forbes, 2023), (NASA, 2023).

To put in a nutshell, experts engaged into the interviews mentioned that as the first category towards methane emission mitigation practice, *accuracy of the reported emission figures* can be provided by *implementing satellite technology for aerial detection and measurement of methane from oil and gas sector* (1) and *employing emission detecting sensors* (2).

The second methane emission abatement category focuses on in*stallation and repairment of tools, devices, and infrastructures* to achieve greenhouse gas emission reduction. Following mitigation practices, reported by

IEA in its *Global Methane Tracker* report, do not only provide effective emission abatement techniques, but also ensure energy efficiency during the processes of these abatement practices. Within this category, four major abatement technology sub-categories are narrated by the experts based on the information from official press releases.

- *Replacement of existing devices*. It has already been widely discussed that traditional oil and gas operations emit significant amounts of methane to the atmosphere. At that point, IEA suggests that these high-emitting equipment must be replaced with more environmentally friendly ones that emit lower amounts of greenhouse gas. Under this sub-category, various specific technical options are available to manage and achieve methane emission abatement:
  - *Using air systems as a power source*: in the oil and gas industry, pressurized natural gas is used as a power source for pumps and controllers. In this process of using natural gas as a power source, methane emission is an inevitable and unavoidable outcome. Instead, pressurized air can be used for the same purpose in oil and gas operations. Different from natural gas, air systems are proven not to leak any methane.
  - *Replacing traditional pumps with electrical pumps*: traditional pumps are widely used in the oil and gas industry throughout the oil & gas value chain. This method uses natural gas as a power source which results in a methane emission. Instead of using traditional pump system, using electrical pumps does not cause methane emission. Electrical pumps use solar and other means of power generators as means of power source, but not natural gas.
  - *Using electric motors*: gas-driven pneumatic devices, gas engines, diesel engines are widely used technologies in oil and gas sector operations such as drilling and well completion. Since these technologies use pressurized natural gas as a power source, gas releases are unavoidable. Indeed, these technologies are referred to as a “low bleed” method since only a little amount of gas is released during their usage. However, there are “zero-bleed” technologies available that use electric motors as a power source instead of pressurized natural gas.

- *Replacing currently used compression technologies*: reciprocating and centrifugal compression technologies are widely used in oil and gas operations. In reciprocating technology, rod packing is used to prevent gas leakage from piston rods which are used to compress gas. However, rod packing is not a fully reliable method since it is likely to fail in preventing gas emission when it gets older. On the other hand, centrifugal compression technology uses spinning turbines to pressurize gas. Seals on the spinning turbine are used to prevent gas leakage. Since wet seals capture and store oil and gas under high pressure, it is either required to be replaced with dry seals or captured oil and gas must be extracted without causing emission.
- *Early device replacement*: gas-driven pneumatic devices are used in oil and gas operations with the purpose of controlling pumps and valves in fluctuating pressure environment. In order to functionally operate, these devices release certain levels of gas and are divided into three categories in terms of the gas release volume: low-bleed, intermitted, and high-bleed. A proper solution to reduce and control emission is to replace high-bleed category devices with low-bleed category as early as possible.

Based on the first category of methane abatement options, replacement of existing devices, governmental level policies, regulations, monitoring, and control systems might be implemented. For instance, usage of natural gas-powered pneumatic devices in oil and gas operations might be prohibited. Additionally, limited emission allowance volume can be implemented based on the performance of the facility.

- The second sub-category of methane abatement option suggests *instalment of new emission control devices instead of replacing the existing ones*:
  - *Installation of Vapor Recovery Units (VRUs)*: VRUs are compressors that collect emissions stored in different parts of the facility which otherwise would be emitted to the atmosphere.
  - *Blowdown capture*: blowdowns are used to depressurize the equipment used in the oil and gas supply chain. Its function is to collect and recover the excess gas which is intended to be stored and sold in the market for economic purposes. So, instead of releasing gas into the atmosphere,

blowdown capture technology helps to store the potential emission and lower investment costs for the installed devices.

- *Installation of plungers*: in the oil and gas sector, as a result of the production process, a certain amount of liquid is stored in producing wells which needs to be extracted and removed in order to provide effective flow of the production. In traditional liquid removal method, called "liquid unloading", production well is opened, and liquid is captured by the operator. In this unloading process, methane stored in the wells leaks to the atmosphere. Installation of plungers is expected to extract well liquids more efficiently and prevent stored methane leakage into the atmosphere.
- *Installation of ventilation systems* is also a well-known method of emission reduction when it comes to the emissions sourced from the coal industry.

Considering the potential effectiveness of new installations to prevent methane emission, governments are encouraged to participate in engaging local firms to the process. By means of command-and-control policies, governments might require installation of the methane emission technologies from local institutions. Additionally, proper usage, durability, and maintenance of the installed equipment might be periodically checked by the government agencies to ensure prevention and control of methane emission.

- *Leak detection and repair* is the third sub-category within the proposed emission abatement strategies. This option includes detection of the fugitive leaking points and their repair. *Using infrared cameras* is a famous technique used in leak detection and repair. The process of leak detection and repair is periodically conducted, and its frequency varies (2023).

All in all, the second category of methane emission reduction strategy, i*nstalment and repairment of tools, devices, and infrastructures* envisages *replacement of existing devices, instalment of new emission control devices, leak detection and repair,* and *other* sub-categories.

<table>
<tr><th>Mitigation strategy category</th><th>Subcategory</th><th>Technical options</th></tr>
<tr><td rowspan="3">Improving the accuracy of the emission data</td><td rowspan="2">Implementing satellites for aerial detection and measurement of methane from oil and gas sector</td><td>GHGSat-D</td></tr>
<tr><td>TROPOMI</td></tr>
<tr><td>Employing emission detecting sensors</td><td>Airborne Visible/Infrared Imaging Spectrometer-Next Generation</td></tr>
<tr><td rowspan="14">Installation and repairment of tools, devices, and infrastructures</td><td rowspan="5">Replacement of existing devices</td><td>Using air systems as a power source</td></tr>
<tr><td>Replacing traditional pumps with electrical pumps</td></tr>
<tr><td>Using electric motors</td></tr>
<tr><td>Replacing currently used compression technologies</td></tr>
<tr><td>Early device replacement</td></tr>
<tr><td rowspan="3">Instalment of new emission control devices instead of replacing the existing ones</td><td>Installation of Vapor Recovery Units (VRUs)</td></tr>
<tr><td>Blowdown capture</td></tr>
<tr><td>Installation of plungers Installation of ventilation systems</td></tr>
<tr><td rowspan="3">Leak detection and repair</td><td>Pellistor sensors</td></tr>
<tr><td>NDIR sensors</td></tr>
<tr><td>MPS sensors</td></tr>
<tr><td rowspan="3">Other</td><td>Installing catalyst that is designed to reduce unburned emission of methane</td></tr>
<tr><td>Application of micro turbines</td></tr>
<tr><td>Conducting pipeline pump-down</td></tr>
</table>

Table 10: Methane abatement strategy category, subcategory, and technical options

To summarize recommendations for methane abatement from energy sources, since emission from oil and gas production, natural gas flaring, coal consumption, and hydroelectricity generation constitute significant sources of emission from energy sector, implementation of above-given strategies constitute important solution to achieve the targeted abatement as reported by the experts supported by the official sources.

Conclusion

Methane, composing 80% of the whole, is an important element of natural gas (YCCC, 2020). While constituting a great potential for renewable energy sources, it is also accepted as a potentially hazardous element of greenhouse gases by causing negative environmental externalities such as global warming and climate change. Although reduction of methane emission concentration in the atmosphere is estimated to cease climate related issues, its concentration is observed to demonstrate a continually increasing trend since pre-industrial periods as supported by various academic studies (e.g. IEA, 2023). Despite methane's potential for softening climate problems, its effect is usually neglected by the global community (Claudia et al., 2009). In this academic study, a comparative analysis of methane emission from energy sources is presented in the case of three countries: Azerbaijan, Kazakhstan, and Russia. Based on both primary and secondary data, emission sources are identified. By employing Multiple Linear Regression analysis, effects of 4 explanatory variables on methane emission from energy sources are tested. Regression results indicate that in Azerbaijan, *total oil and natural gas production, coal consumption*, and *natural gas flaring* positively contributes to methane emission while *hydroelectricity generation* demonstrates no significant effect. On the other hand, *total oil and natural gas production, coal consumption,* and *hydroelectricity generation* indicate positive effect on CH_4 emission for Kazakhstan whereas no significant effect of *natural gas flaring* is found. Eventually, regression analysis concludes that all three tested variables, *total oil and natural gas production, coal consumption,* and *hydroelectricity,* have positive effect on methane emission from energy sector in Russia although effect of *natural gas flaring* on methane emission could not be tested due to country-specific data unavailability. Finally, along with the specific mitigation techniques and practices, the study also provides two main categories of methane emission mitigation strategy: *ensuring accuracy of the reported emission figures* and *installation and repairment of tools, devices, and infrastructures*.

While it provides up-to-date analysis of specific variables and their effect on a greenhouse gas which has long been ignored by the global community despite its hazardous potential, this study also contains significant research limitations which are recommended to be eliminated in further analysis. The main limitation of the study is absence of the officially reported long-term data for variables of interest which is assumed to result in invalid interpretations from statistical modelling. Specifically, only 30 years' methane emission data is available for selected countries. Moreover, one specific variable's (flaring from natural gas) data is not found for Russia. Additionally, *the Recommendations* section of the study lacks in providing recommendations regarding emitting methane from hydroelectricity sector.

The focus of the further studies in this area is recommended to include a greater number of variables regarding the energy sector for the selected countries (e.g. stationary, mobile, and bio combustion data). Furthermore, the possibility to gather longer-term historical data for interested variables should also be analyzed more sophisticatedly. Lastly, further research studies should also focus on providing recommendations regarding emitting methane from the hydroelectricity sector.

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Appendix 1: Correlation Matrixes

Source: Authors' compilation from Microsoft Excel

Correlation table for total oil production and natural gas production: Azerbaijan

	Total oil production (tons)	*Total Gas Production (billion cubic meters)*
Total oil production (tons)	1	
Total Gas Production (billion cubic meters)	**0,850715452**	1

Correlation table for total oil production and natural gas production: Kazakhstan

	Total oil production (tons)	*Total Gas Production (billion cubic meters)*
Total oil production (tons)	1	
Total Gas Production (billion cubic meters)	**0, 985091688**	1

Correlation table for total oil production and natural gas production: Russia

	Total oil production (tons)	*Total Gas Production (billion cubic meters)*
Total oil production (tons)	1	
Total Gas Production (billion cubic meters)	**0, 808724274**	1

Appendix 2: Interview details

1) Interview with the high-level representative from "Təmiz Şəhər" OJSC

Interviewer	Interviewee	Workplace	Background	Interview Format	Interview language
Elshan Yusifli	Mr. Elnur Aliyev	"Təmiz Şəhər" OJSC	- PhD in Geography - Professor in Baku Engineering University	Online	Azerbaijani

Interview questions
What are the main factors and processes causing methane emission?
Why achieving reduction in the volume of methane emission is important?
In the practice of "Təmiz Şəhər" OJSC, what actions are being taken to achieve reduction in methane emission?
How important is the involvement of technology in achieving reduction in methane emission?
What are the ways to achieve methane emission reduction?
In comparison with Europe region, how would you evaluate the performance of Azerbaijan in fighting against methane emission? Do you think if we lack certain competencies as a country in this matter?

2) Interview with the Ecology expert

Interviewer	Interviewee	Workplace	Background	Interview Format	Interview language
Elshan Yusifli	Mr. Masud Abdullayev	“Safe Point” CJSC	- Master of Applied Ecology from Eötvös Loránd University - Bachelor of Ecology from Baku State University	Online	Azerbaijani

Interview questions
How severe is the case of methane emission accepted in Azerbaijan? What are the reasons if yes?
What are the main factors triggering methane emission in Azerbaijan?
In comparison with the level of actions taken to mitigate CO_2, do you think enough attention is paid to methane emission mitigation in the country?
In the practice of businesses as well as in social fields, what important actions are taken to mitigate methane emission?
Is there any available information regarding negative effects of methane emission on human health?
What are the ways to achieve methane emission reduction?
In comparison with Europe region, how would you evaluate the performance of Azerbaijan in fighting against methane emission? Do you think if we lack certain competencies as a country in this matter?

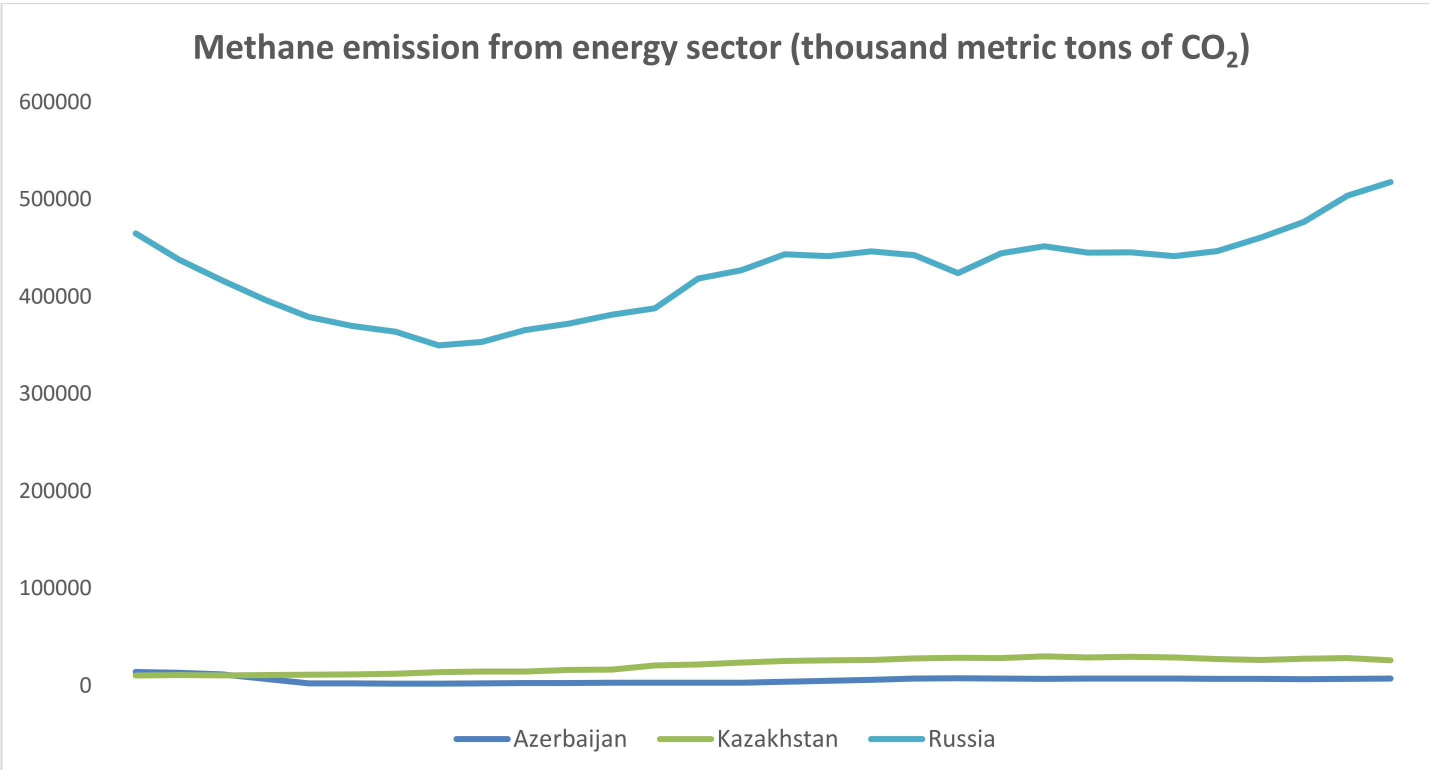
3) Interview with an HSE (health, safety, and environment) expert

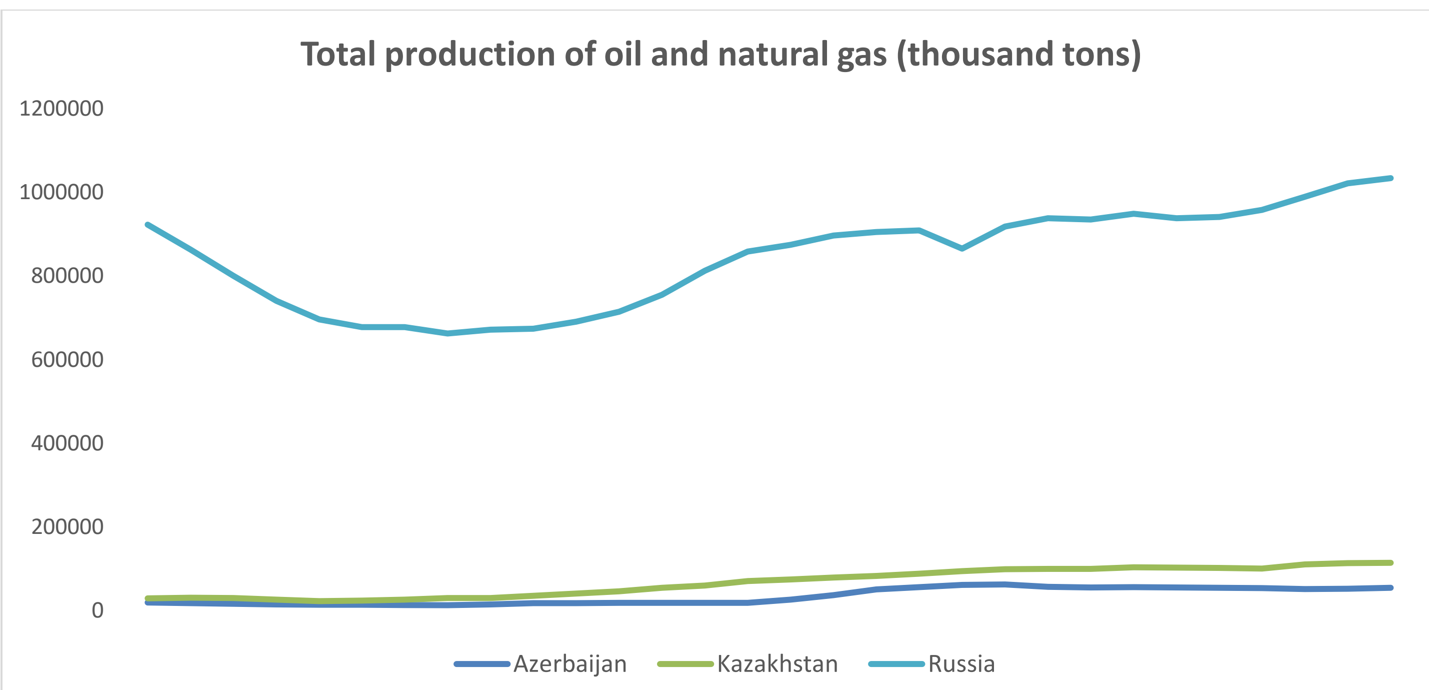
Interviewer	Interviewee	Workplace	Background	Interview Format	Interview language
Elshan Yusifli	Confidential participant	Macro-level company in energy market	Health, safety, and environment experience	Online	Azerbaijani

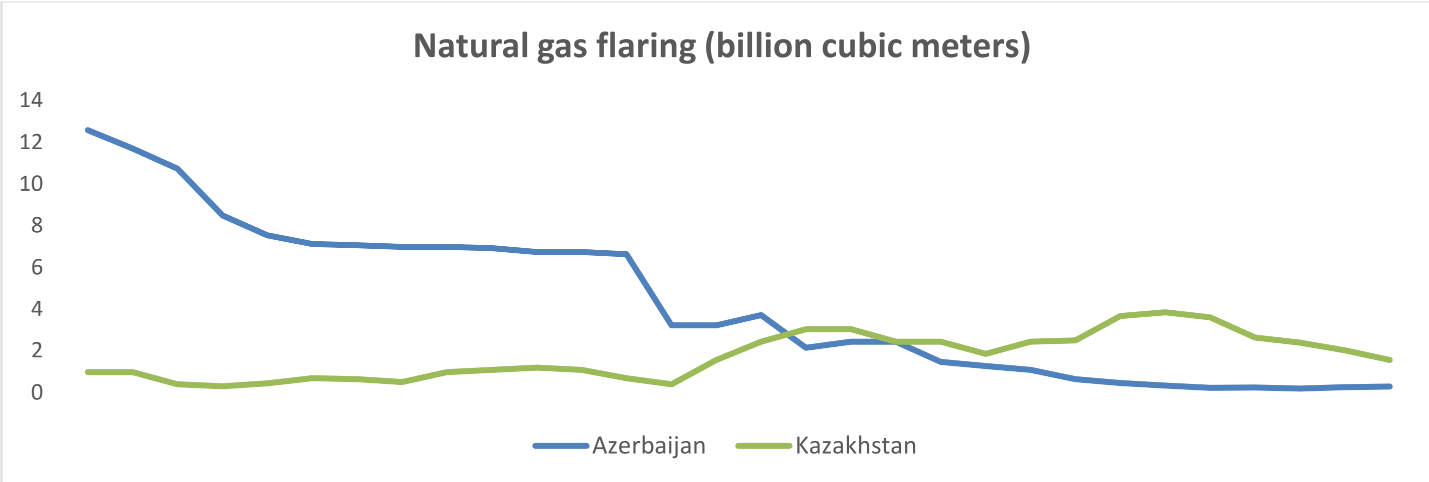
Interview questions
How severe is the case of methane emission accepted in Azerbaijan? What are the reasons if yes?
What are the main factors triggering methane emission in Azerbaijan?
In comparison with the level of actions taken to mitigate CO_2, do you think enough attention is paid to methane emission mitigation in the country?
In the practice of businesses as well as in social fields, what important actions are taken to mitigate methane emission?
Is there any available information regarding negative effects of methane emission on human health?
What are the ways to achieve methane emission reduction?
In comparison with Europe region, how would you evaluate the performance of Azerbaijan in fighting against methane emission? Do you think if we lack certain competencies as a country in this matter?

Appendix 3: Graphical visualization of historical figures for study variables (1990-2019)

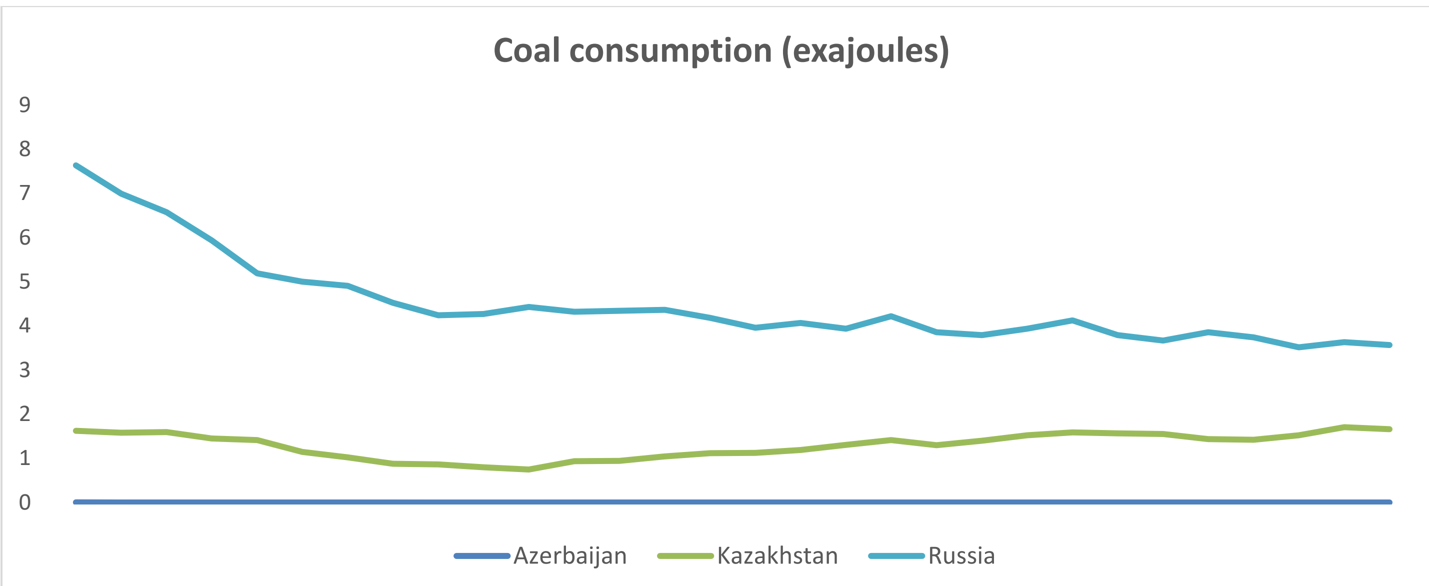
Source: Author's compilation from Microsoft Excel

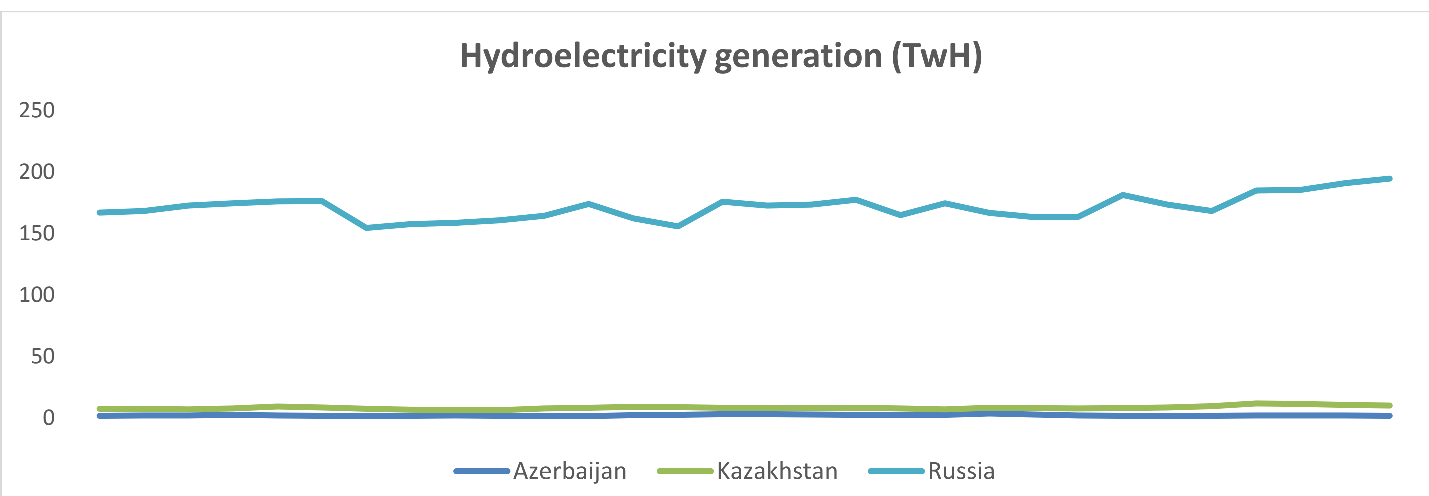






[1]

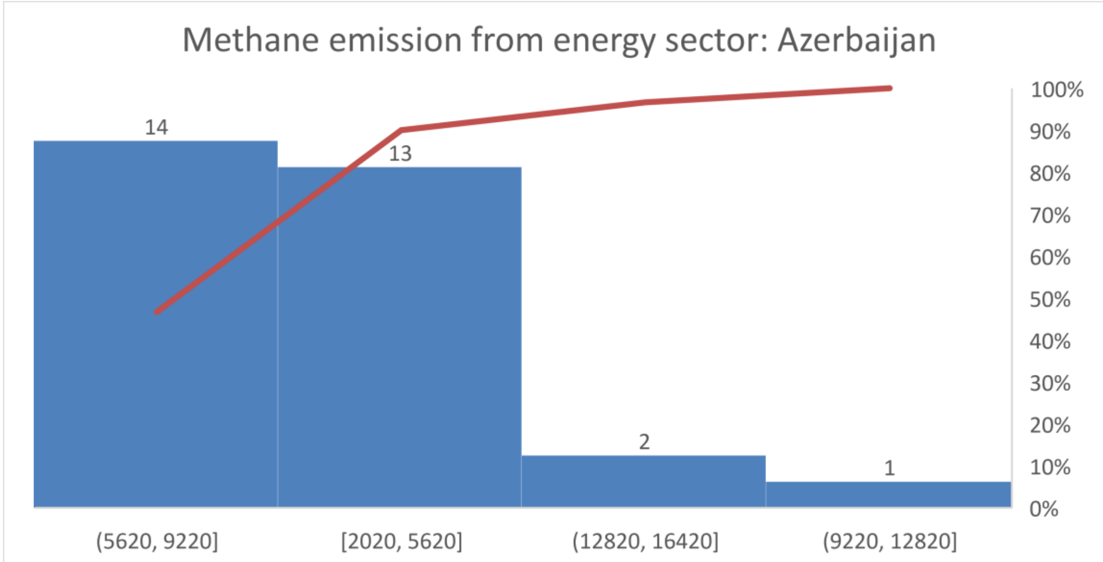


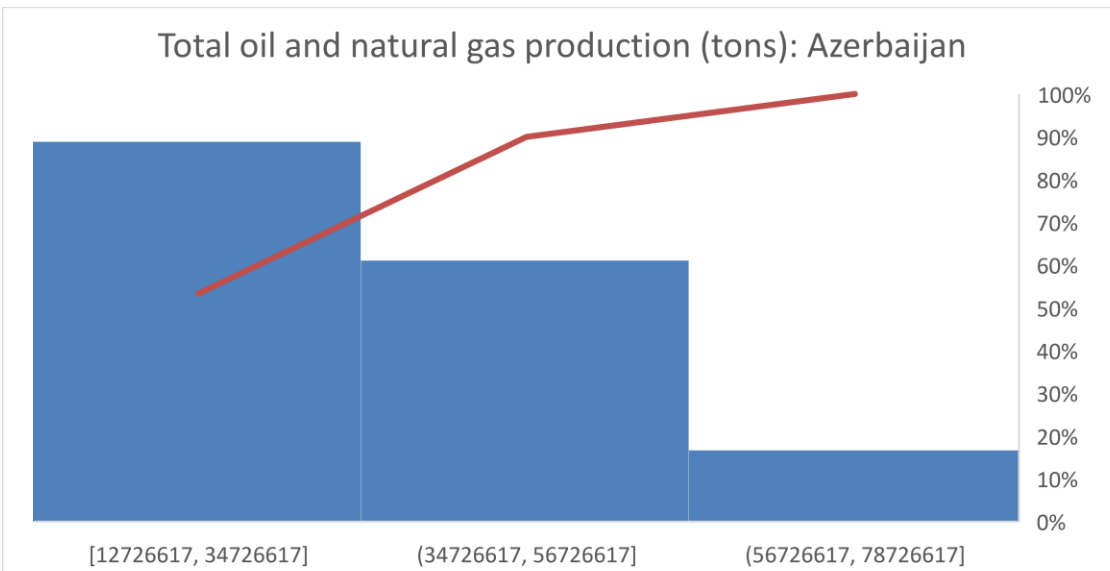


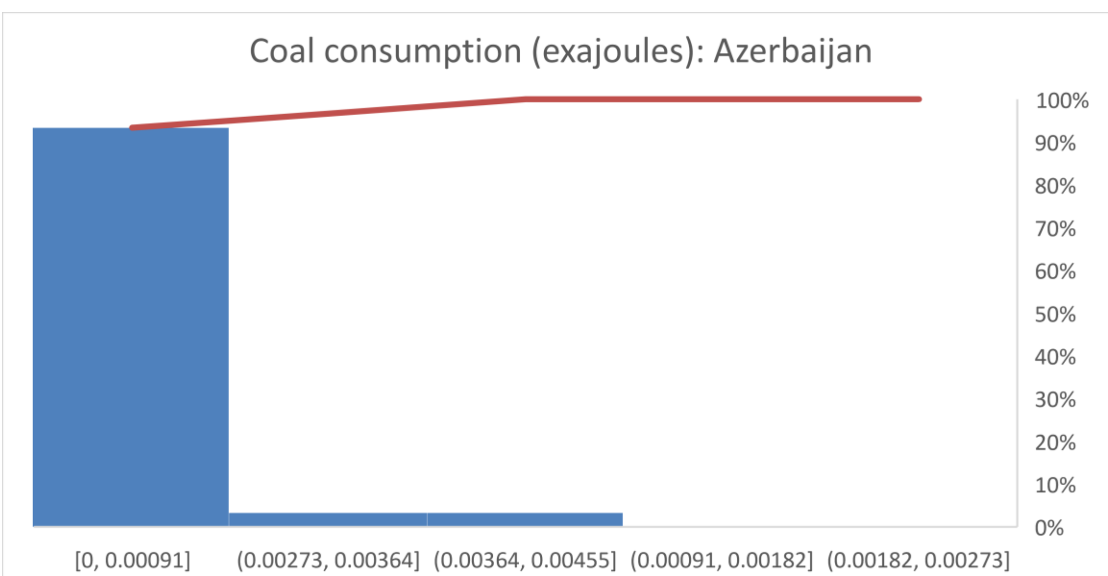
[1] Natural gas flaring data is not available for Russia

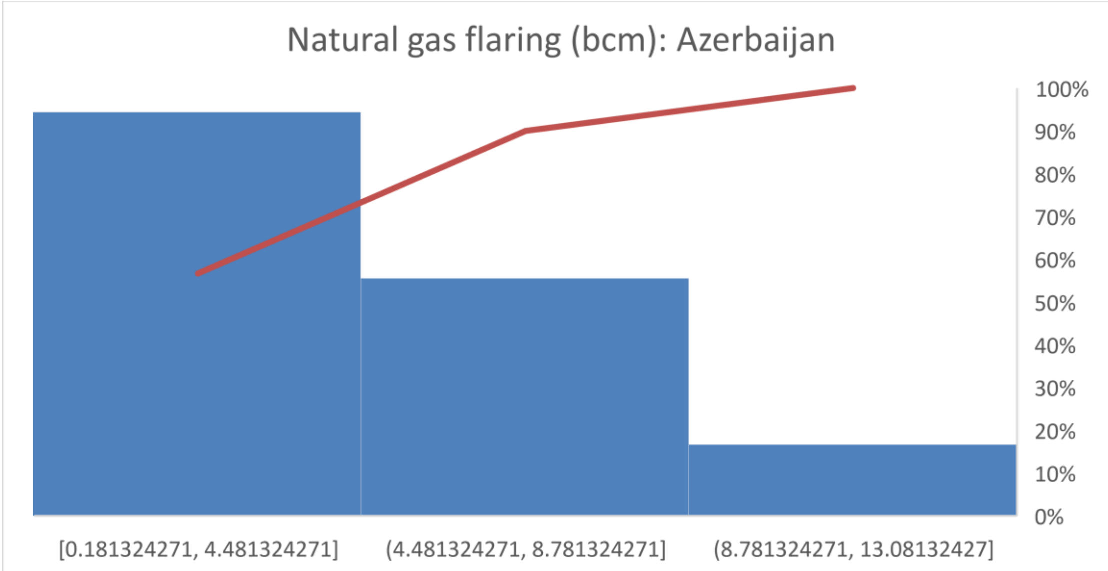
Appendix 4: Distribution of values by frequency grouped by intervals (Histograms)

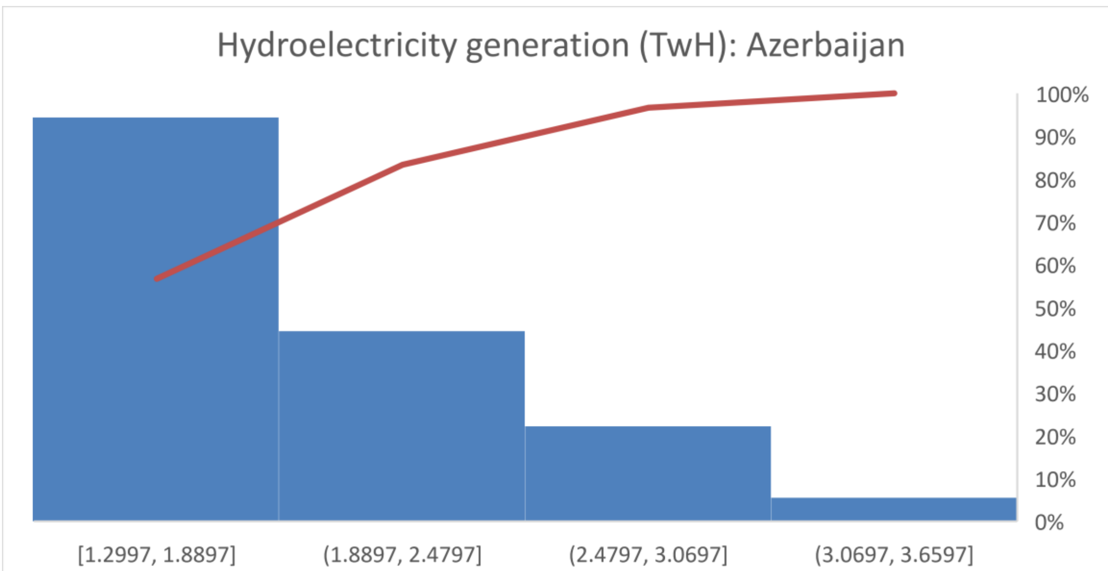
Source: Author's compilation from Microsoft Excel

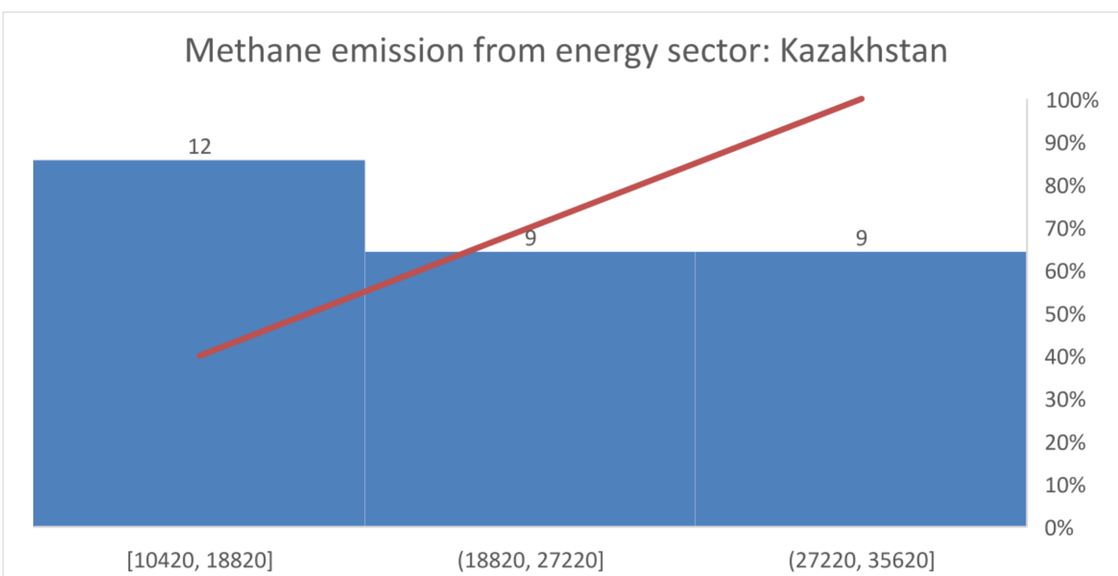


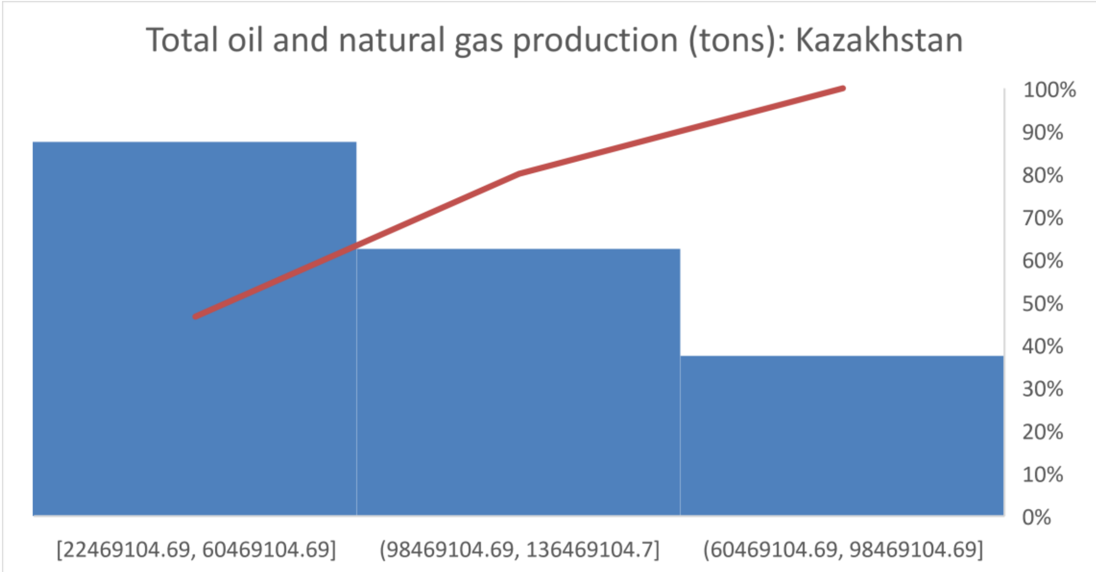


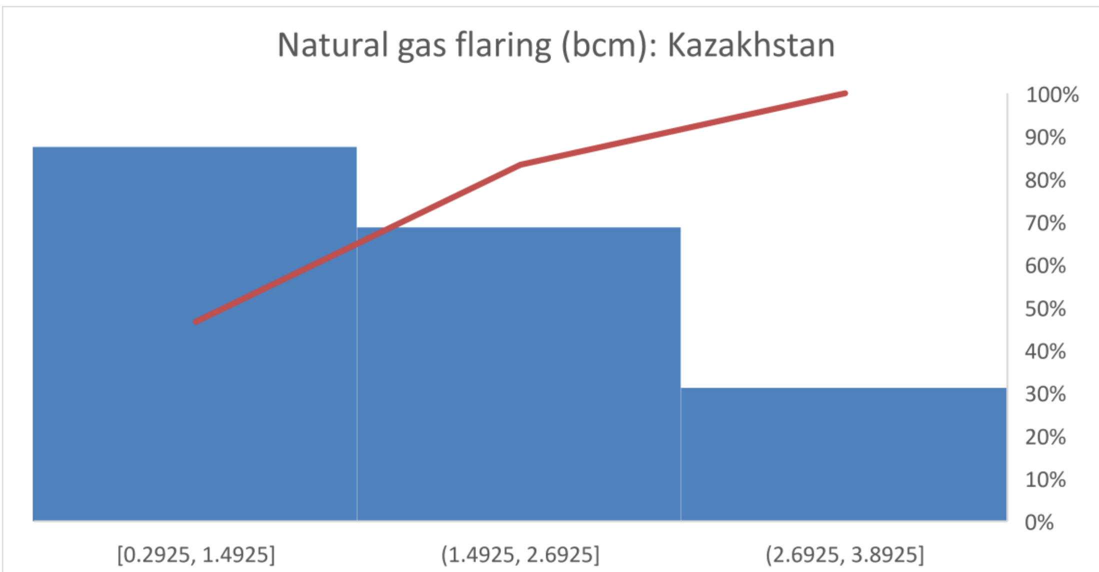


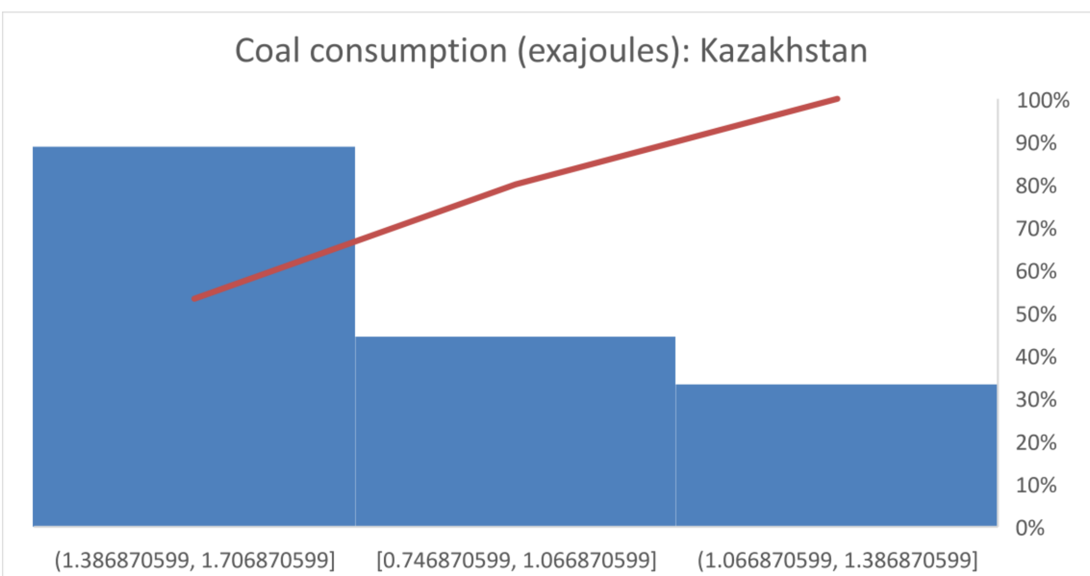

Natural gas flaring (bcm): Azerbaijan
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
[0.181324271, 4.481324271]
(4.481324271, 8.781324271]
(8.781324271, 13.08132427]

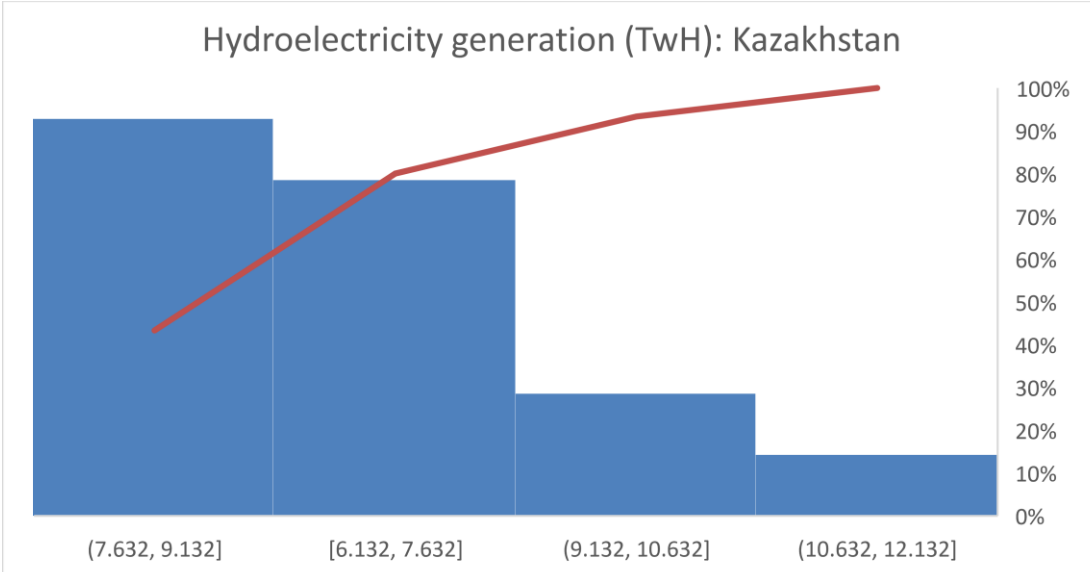

Hydroelectricity generation (TwH): Azerbaijan
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
[1.2997, 1.8897]
(1.8897, 2.4797]
(2.4797, 3.0697]
(3.0697, 3.6597]

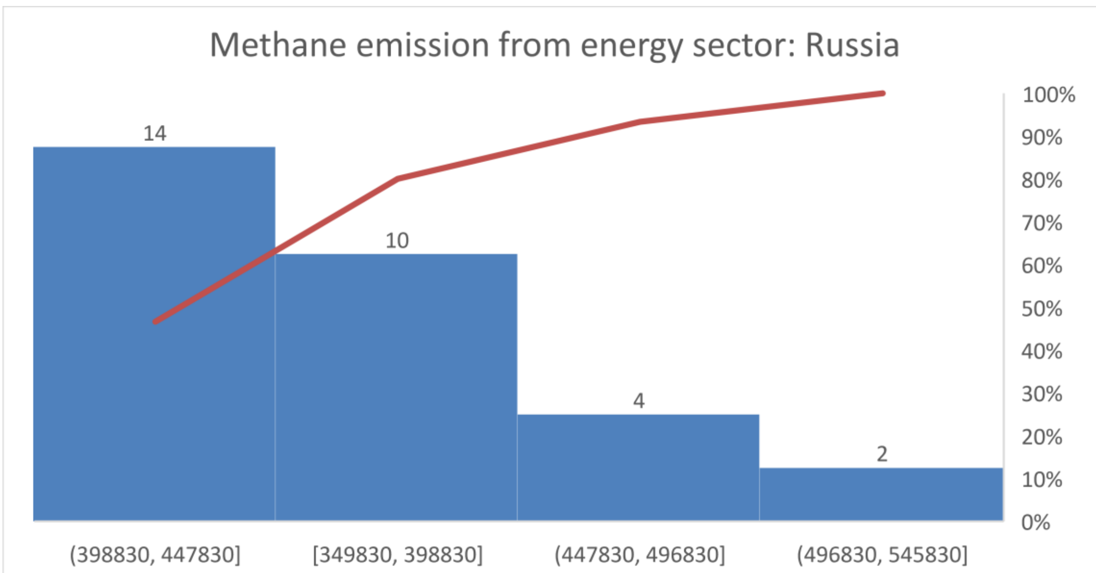

Methane emission from energy sector: Kazakhstan
12
9
9
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
[10420, 18820]
(18820, 27220]
(27220, 35620]

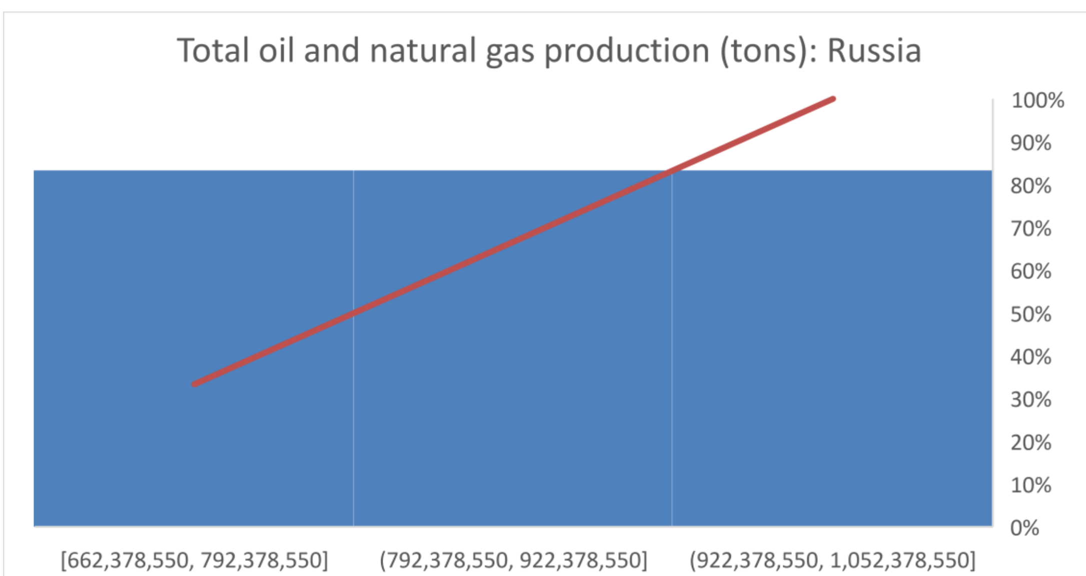

Total oil and natural gas production (tons): Kazakhstan
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
[22469104.69, 60469104.69]
(98469104.69, 136469104.7]
(60469104.69, 98469104.69]

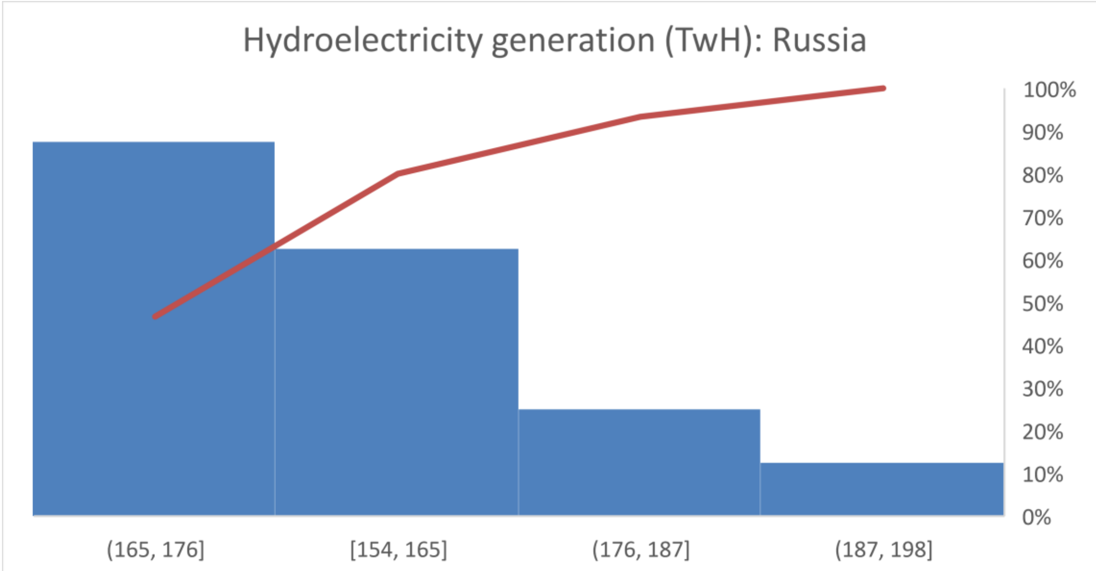

Natural gas flaring (bcm): Kazakhstan
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
[0.2925, 1.4925]
(1.4925, 2.6925]
(2.6925, 3.8925]

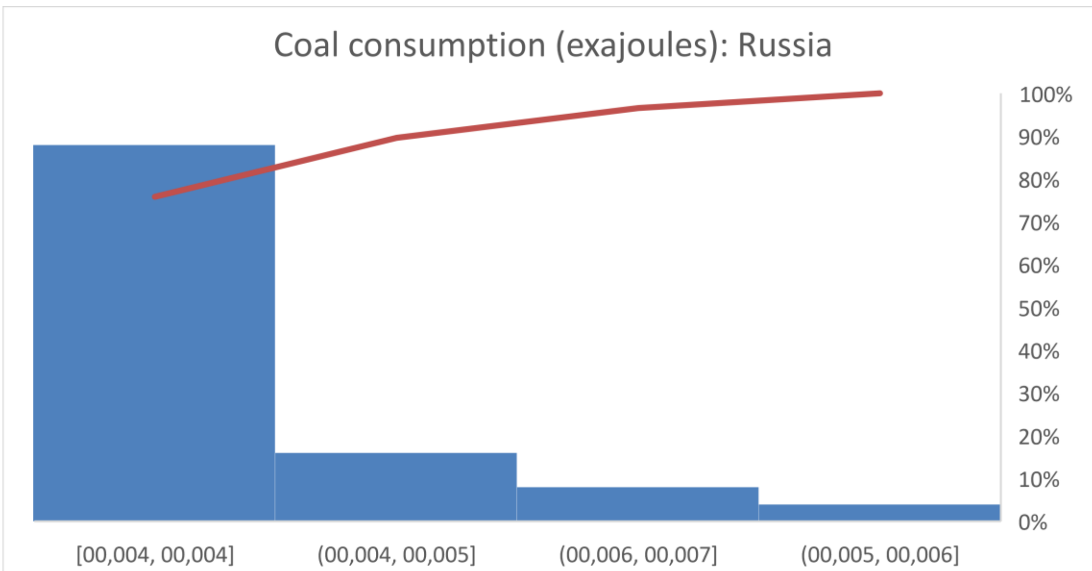

Coal consumption (exajoules): Kazakhstan
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
(1.386870599, 1.706870599]
[0.746870599, 1.066870599]
(1.066870599, 1.386870599]


Hydroelectricity generation (TwH): Kazakhstan
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
(7.632, 9.132]
[6.132, 7.632]
(9.132, 10.632]
(10.632, 12.132]


Methane emission from energy sector: Russia
14
10
4
2
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
(398830, 447830]
[349830, 398830]
(447830, 496830]
(496830, 545830]

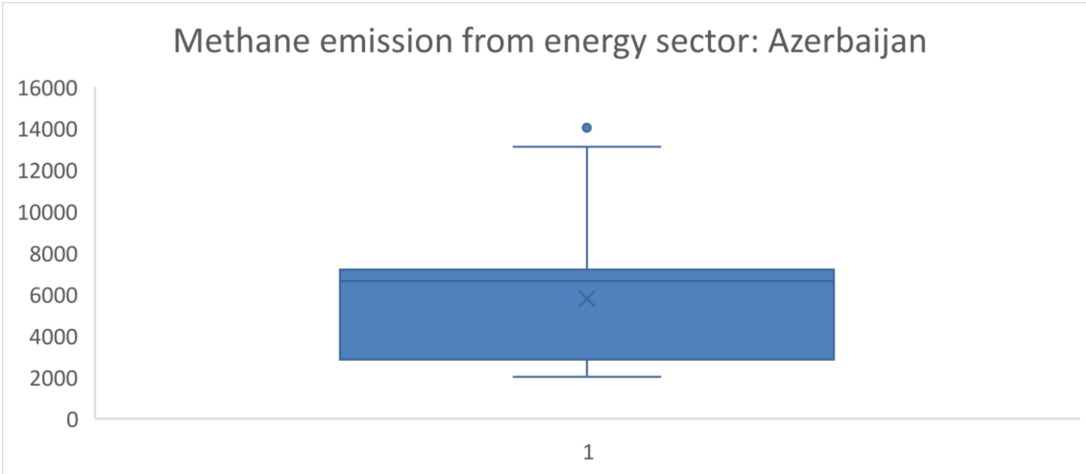

Total oil and natural gas production (tons): Russia
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
[662,378,550, 792,378,550]
(792,378,550, 922,378,550]
(922,378,550, 1,052,378,550]

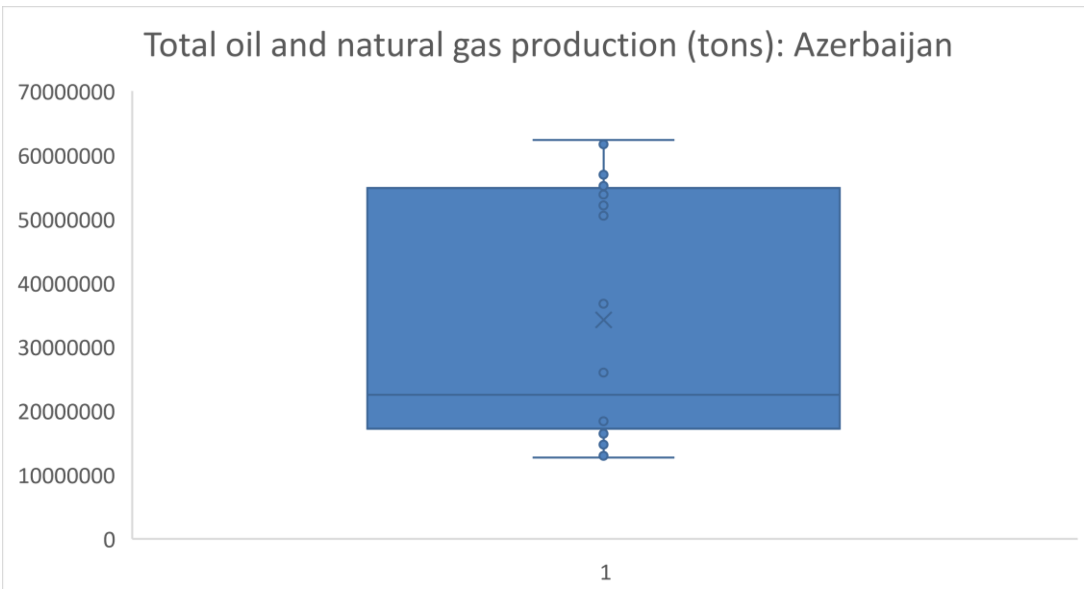

Hydroelectricity generation (TwH): Russia
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
(165, 176]
[154, 165]
(176, 187]
(187, 198]

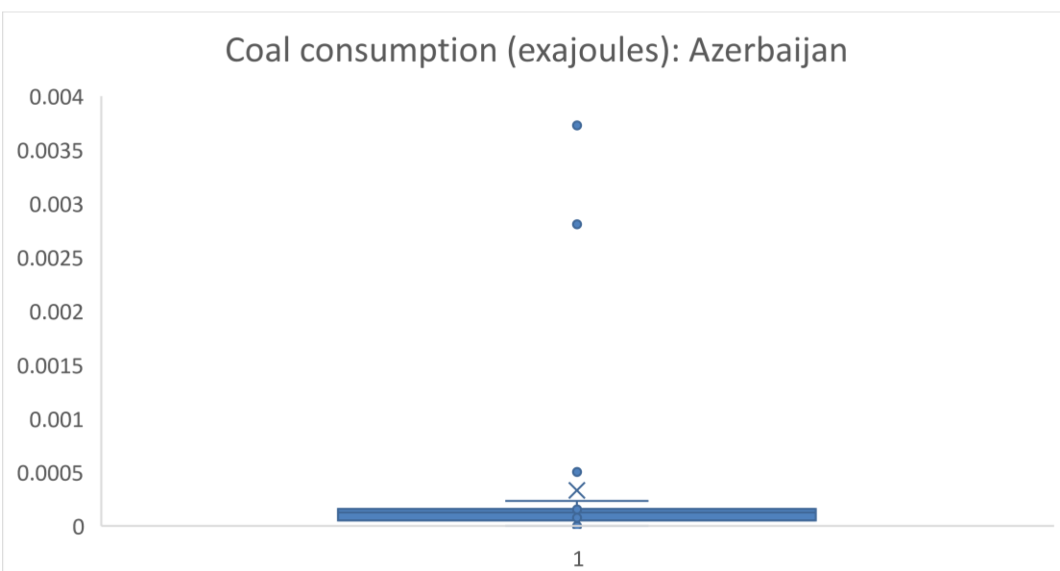

Coal consumption (exajoules): Russia
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
[00,004, 00,004]
(00,004, 00,005]
(00,006, 00,007]
(00,005, 00,006]

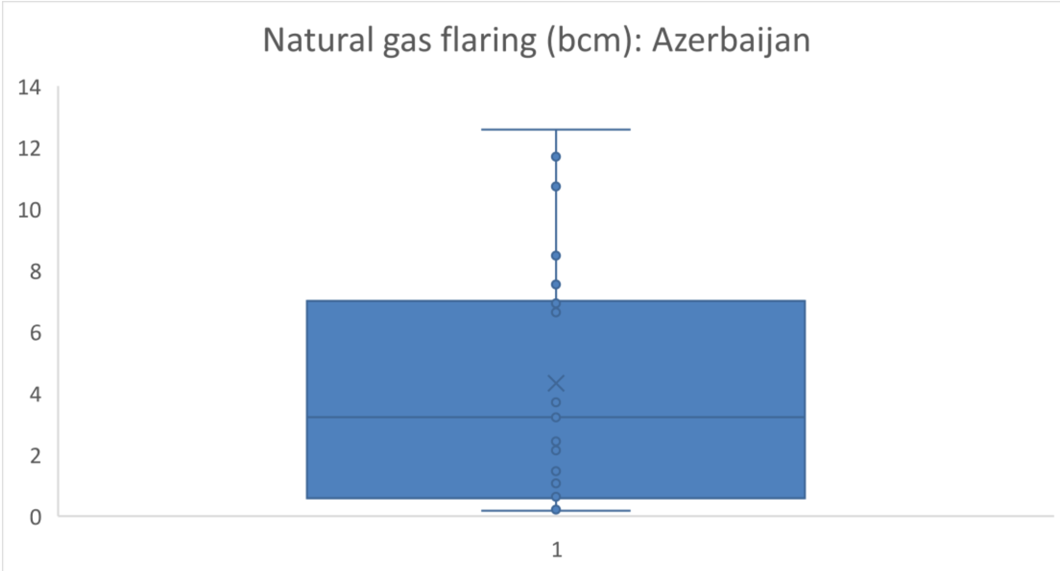
Appendix 5: Graphical illustration of outliers/anomalies (Boxplots)

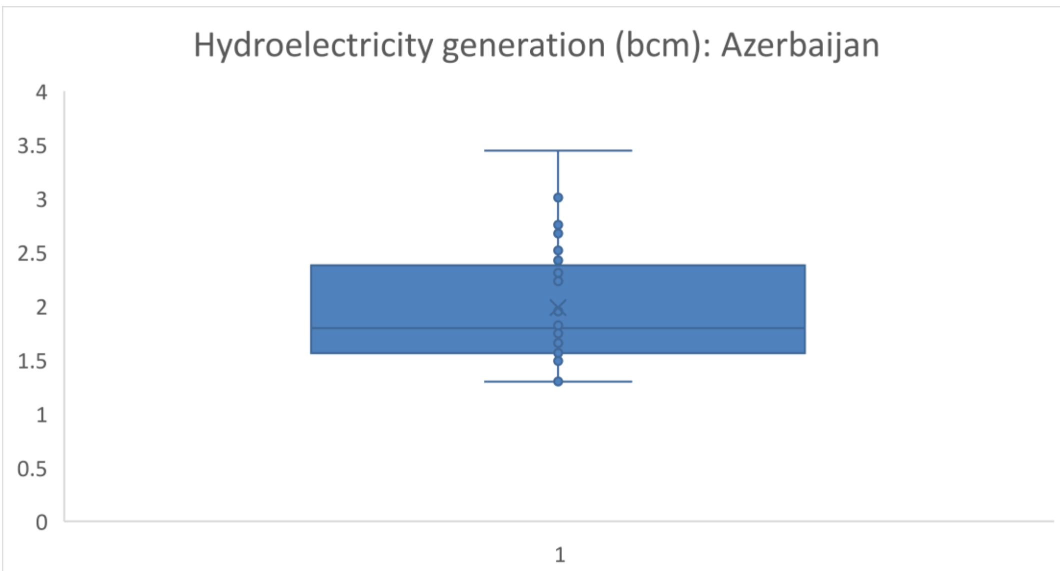
Source: Author's compilation from Microsoft Excel

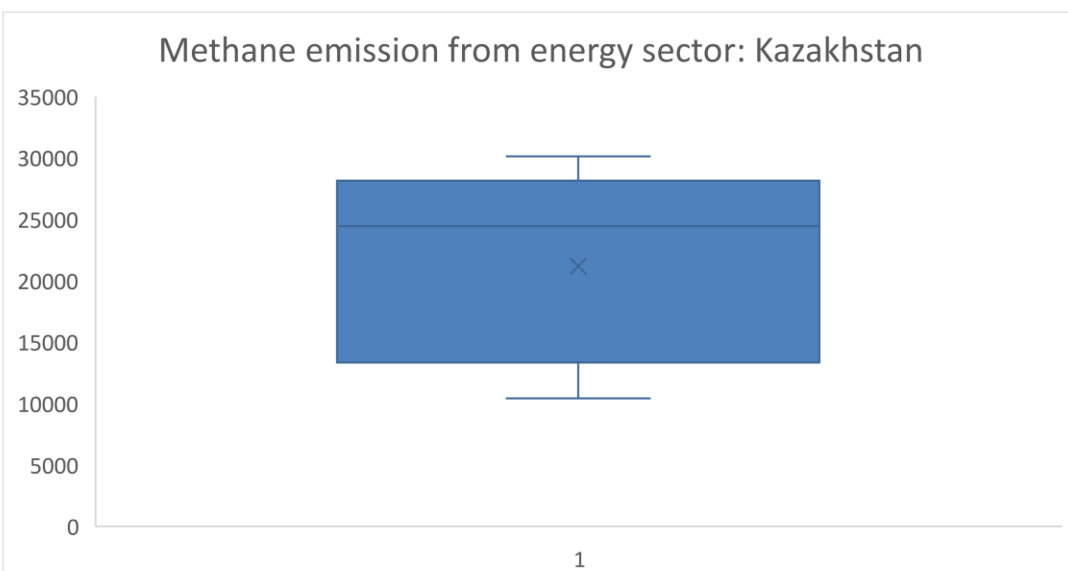


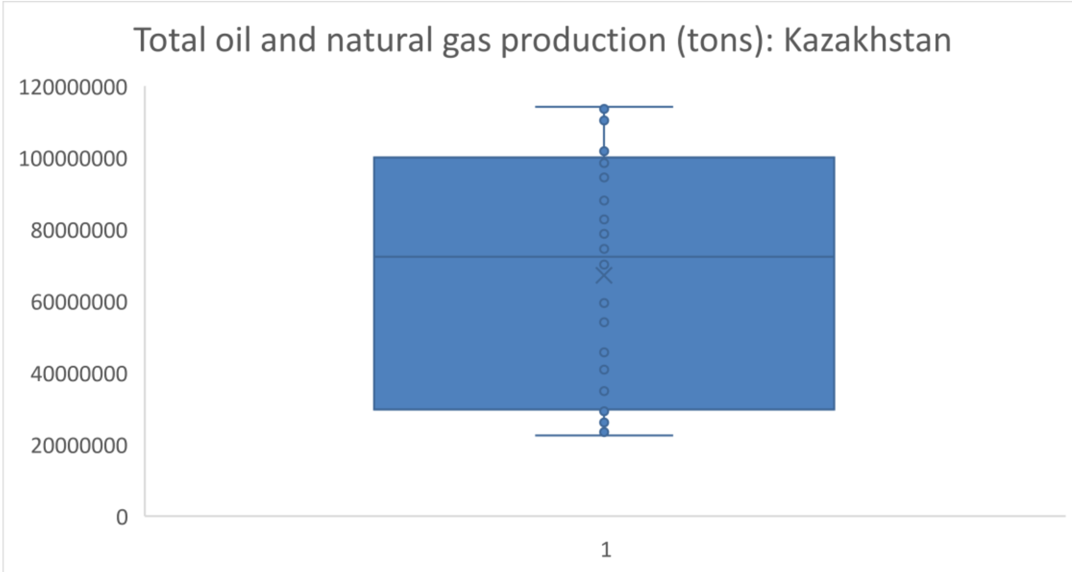


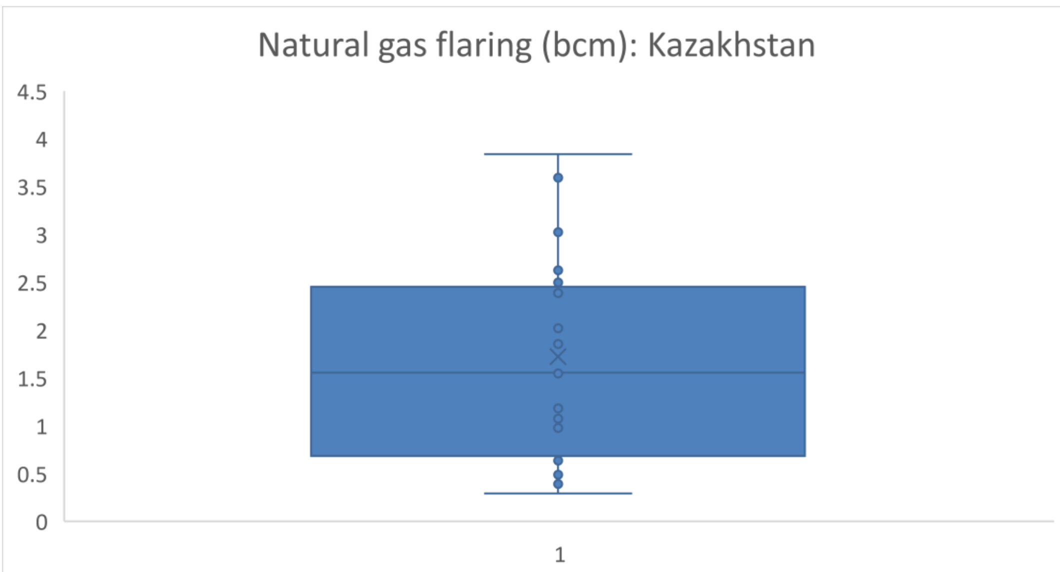


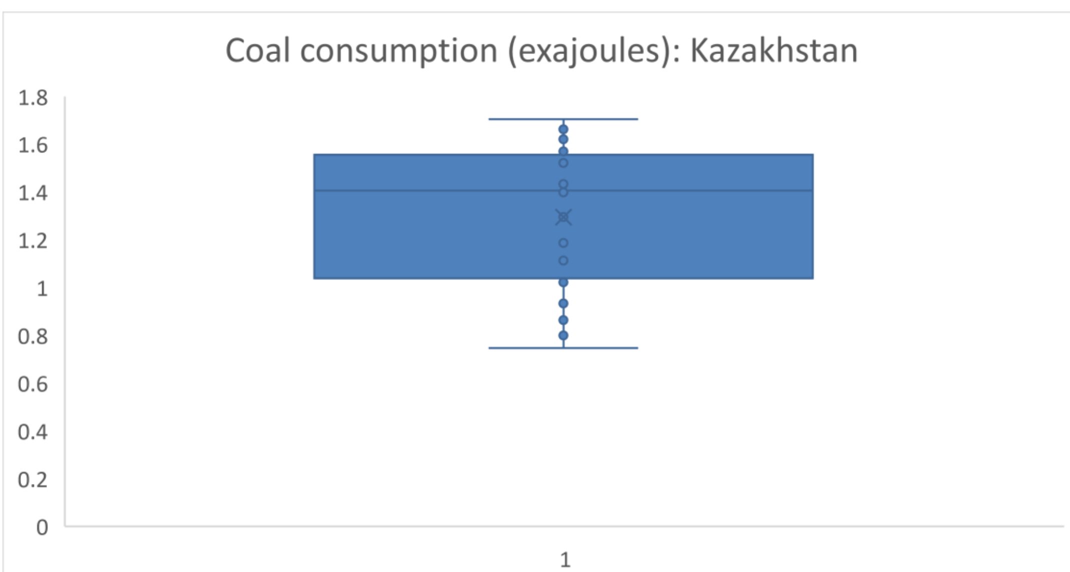

Natural gas flaring (bcm): Azerbaijan
14
12
10
8
6
4
2
0
1

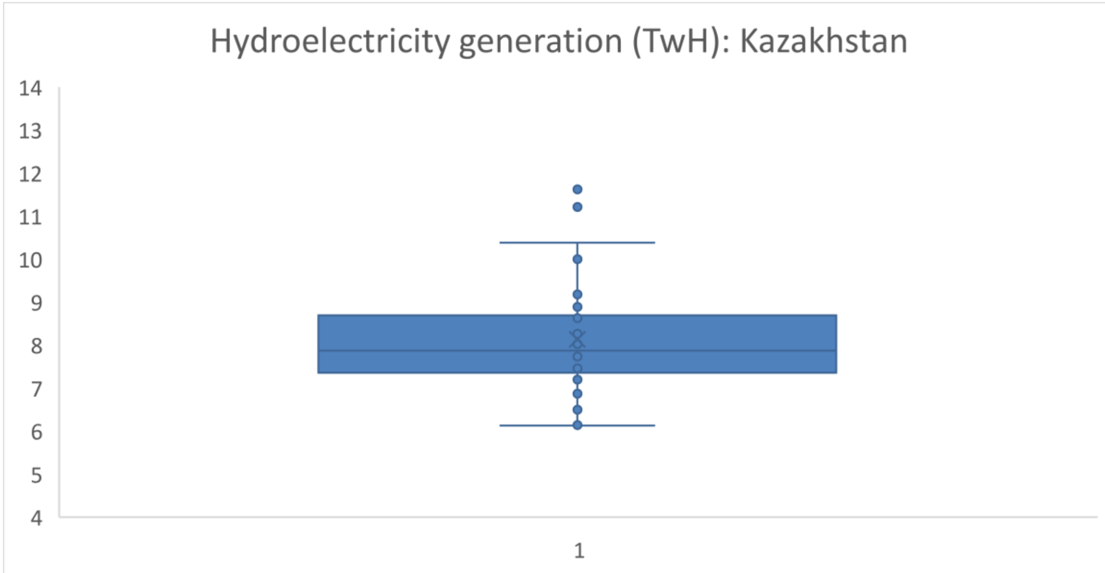

Hydroelectricity generation (bcm): Azerbaijan
4
3.5
3
2.5
2
1.5
1
0.5
0
1

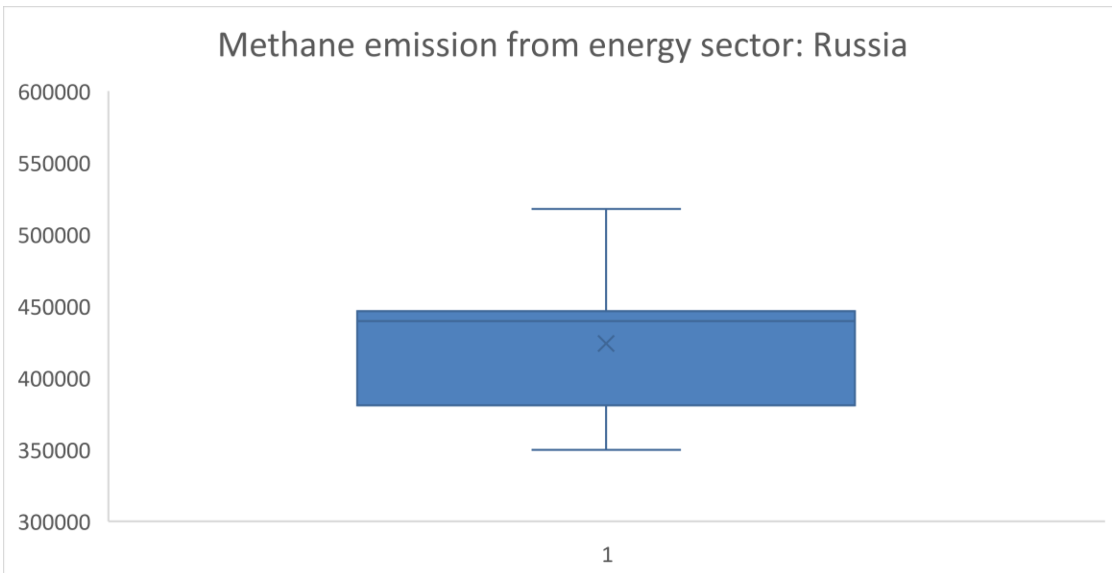

Methane emission from energy sector: Kazakhstan
35000
30000
25000
20000
15000
10000
5000
0
1

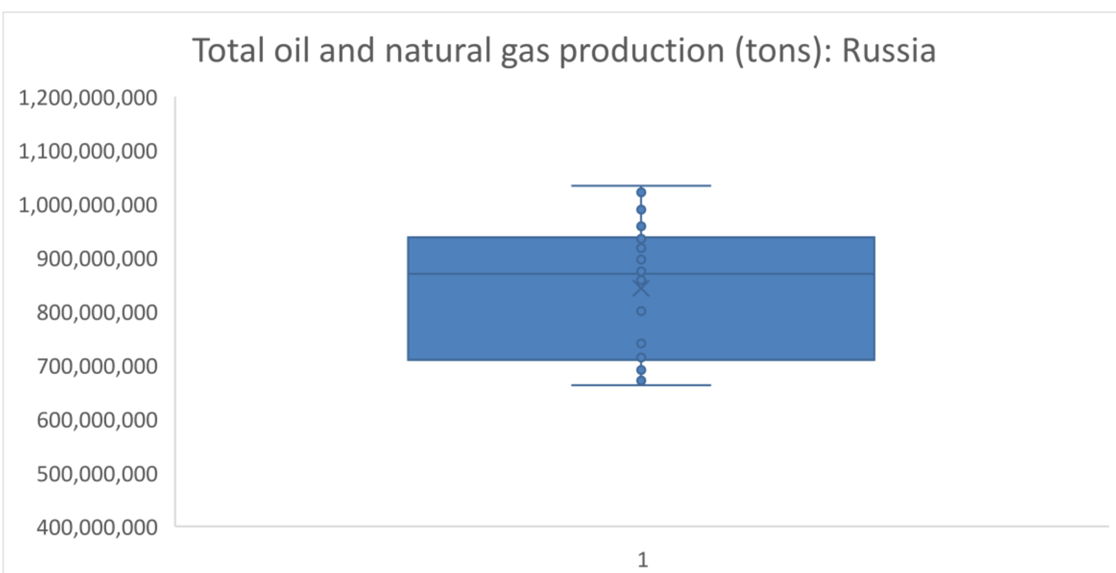

Total oil and natural gas production (tons): Kazakhstan
120000000
100000000
80000000
60000000
40000000
20000000
0
1

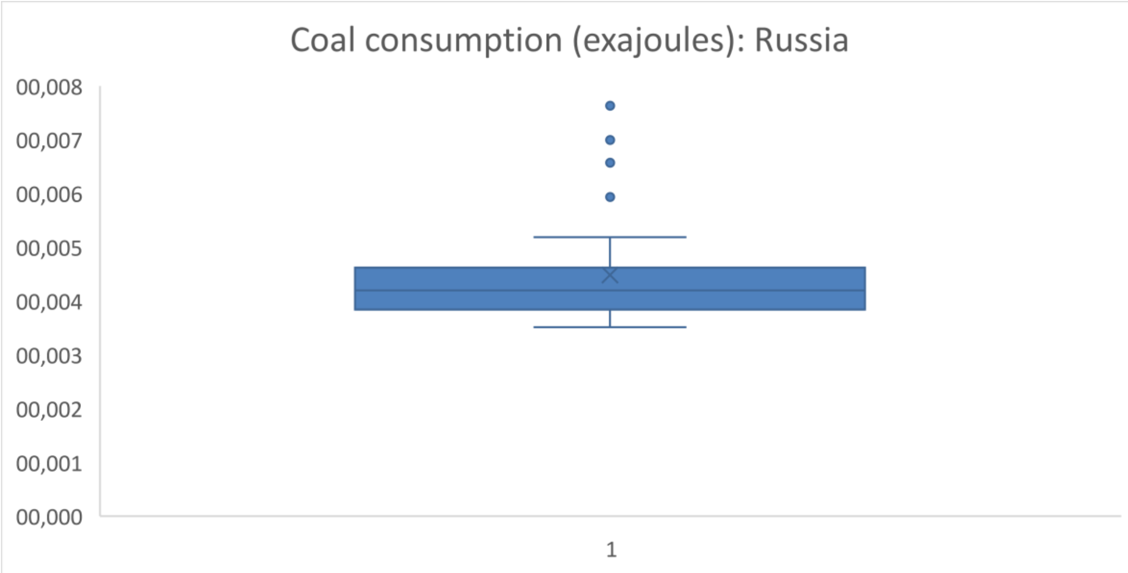

Natural gas flaring (bcm): Kazakhstan
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
1

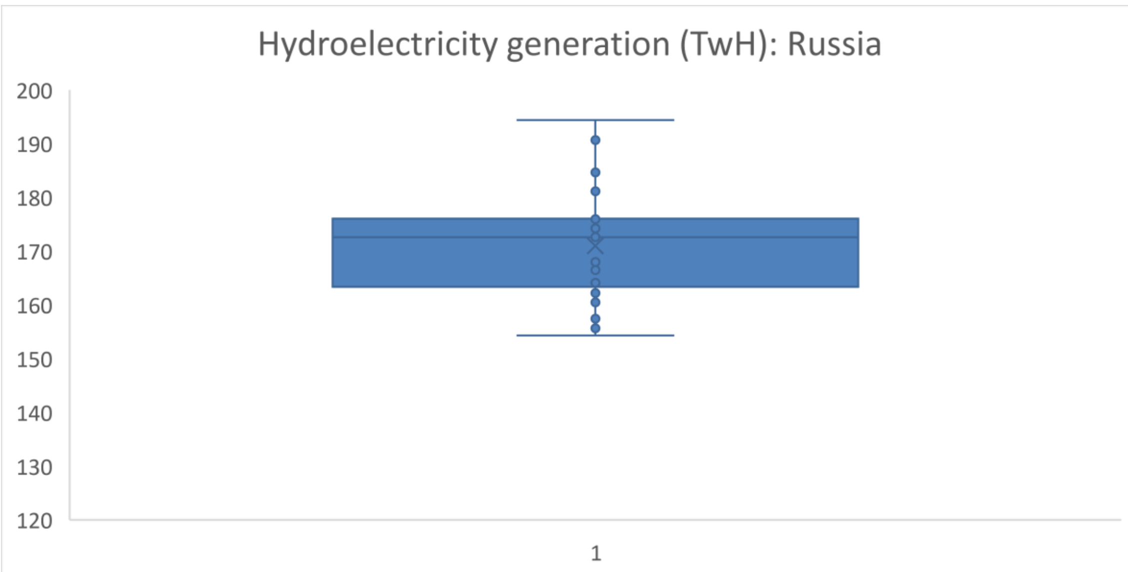

Coal consumption (exajoules): Kazakhstan
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1


Hydroelectricity generation (TwH): Kazakhstan
14
13
12
11
10
9
8
7
6
5
4
1


Methane emission from energy sector: Russia
600000
550000
500000
450000
400000
350000
300000
1

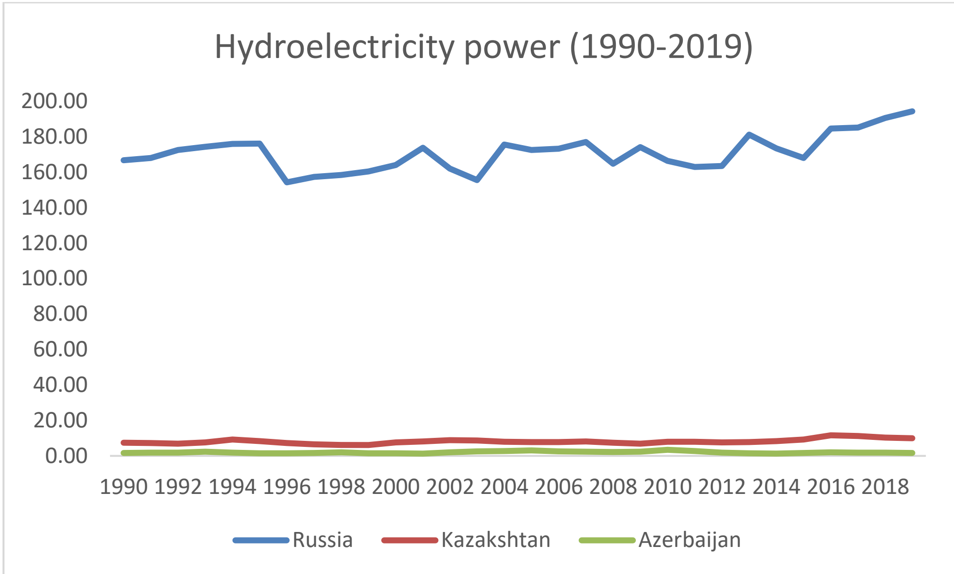

Total oil and natural gas production (tons): Russia
1,200,000,000
1,100,000,000
1,000,000,000
900,000,000
800,000,000
700,000,000
600,000,000
500,000,000
400,000,000
1


Coal consumption (exajoules): Russia
00,008
00,007
00,006
00,005
00,004
00,003
00,002
00,001
00,000
1


Hydroelectricity generation (TwH): Russia
200
190
180
170
160
150
140
130
120
1

Appendix 6: Hydroelectricity power by country (1990-2019)

Source: Author's compilation from Microsoft Excel



Appendix 7: VIFs by country

Source: Author's compilation from Stata 13

Table 10: VIF (Azerbaijan)

Variable	VIF	1/VIF
Naturalgas~b	8.53	0.117229
TotalOilan~n	5.87	0.170291
Coalconsum~J	2.52	0.396937
Hydroelect~H	1.06	0.945825
Mean VIF	4.49	

Table 11: VIF (Kazakhstan)

Variable	VIF	1/VIF
TotalOilan~n	4.75	0.210526
Naturalgas~g	3.45	0.289955
Hydroelect~H	1.67	0.597247
Coalconsum~J	1.39	0.718357
Mean VIF	2.82	

Table 12: VIF (Russia)

Variable	VIF	1/VIF
TotalOilan~n	1.58	0.631427
Hydroelect~H	1.52	0.658857
Coalconsum~J	1.11	0.897968
Mean VIF	1.41	

Appendix 8: Breusch–Pagan test results for homoscedasticity

Source: Author's compilation from Stata 13

```
. reg e2 TotalOilandGasproductionton CoalconsumptionEJ Naturalgasflaringbillioncub HydroelectricitygenerationTwH

      Source |       SS       df       MS              Number of obs =      30
-------------+------------------------------           F(  4,    25) =    4.16
       Model |  1.8352e+14     4  4.5880e+13           Prob > F      =  0.0102
    Residual |  2.7559e+14    25  1.1024e+13           R-squared     =  0.3997
-------------+------------------------------           Adj R-squared =  0.3037
       Total |  4.5911e+14    29  1.5831e+13           Root MSE      =  3.3e+06
```

e2	Coef.	Std. Err.	t	P>|t|	[95% Conf.	Interval]
TotalOilandGasproductionton	.2043372	.0770204	2.65	0.014	.0457107	.3629637
CoalconsumptionEJ	-3.58e+09	1.20e+09	-2.97	0.006	-6.06e+09	-1.10e+09
Naturalgasflaringbillioncub	1771048	475795.2	3.72	0.001	791129.4	2750966
HydroelectricitygenerationTwH	625903.4	1205274	0.52	0.608	-1856405	3108212
_cons	-1.29e+07	5100867	-2.53	0.018	-2.34e+07	-2421226

Breusch-Pagan test result for Azerbaijan: P-value > 0.01

```
. reg e2 TotalOilandGasproductionton Naturalgasflaring CoalconsumptionEJ HydroelectricitygenerationTwH

      Source |       SS       df       MS              Number of obs =      30
-------------+------------------------------           F(  4,    25) =    1.85
       Model |  3.2036e+13     4  8.0090e+12           Prob > F      =  0.1502
    Residual |  1.0802e+14    25  4.3208e+12           R-squared     =  0.2287
-------------+------------------------------           Adj R-squared =  0.1053
       Total |  1.4006e+14    29  4.8295e+12           Root MSE      =  2.1e+06
```

e2	Coef.	Std. Err.	t	P>|t|	[95% Conf.	Interval]
TotalOilandGasproductionton	.0509558	.0251265	2.03	0.053	-.000793	.1027047
Naturalgasflaring	-1541032	661016.8	-2.33	0.028	-2902422	-179642.2
CoalconsumptionEJ	-1314388	1583272	-0.83	0.414	-4575198	1946422
HydroelectricitygenerationTwH	80733.53	376353.7	0.21	0.832	-694381.5	855848.5
_cons	1964484	2861250	0.69	0.499	-3928371	7857338

Breusch-Pagan test result for Kazakhstan: P-value > 0.01

```
. reg e2 TotalOilandGasproductionton HydroelectricitygenerationTwH CoalconsumptionEJ

      Source |       SS       df       MS              Number of obs =      30
-------------+------------------------------           F(  3,    26) =    2.80
       Model |  5.9752e+16     3  1.9917e+16           Prob > F      =  0.0596
    Residual |  1.8471e+17    26  7.1042e+15           R-squared     =  0.2444
-------------+------------------------------           Adj R-squared =  0.1572
       Total |  2.4446e+17    29  8.4297e+15           Root MSE      =  8.4e+07
```

e2	Coef.	Std. Err.	t	P>|t|	[95% Conf.	Interval]
TotalOilandGasproductionton	.1637654	.1670784	0.98	0.336	-.1796692	.5072
HydroelectricitygenerationTwH	2025016	1934649	1.05	0.305	-1951711	6001743
CoalconsumptionEJ	-1.94e+07	1.61e+07	-1.20	0.239	-5.24e+07	1.37e+07
_cons	-3.45e+08	3.03e+08	-1.14	0.265	-9.67e+08	2.77e+08

Breusch-Pagan test result for Russia: P-value > 0.01

Appendix 9: Global energy-related methane emissions by region reported to the UNFCC and estimates from IEA.

Source: International Energy Agency