NATIONAL AND EU GAS SUPPLY SECURITY IN-BETWEEN GEOPOLITICS AND ENERGY INFRASTRUCTURES

Master's Degree in Georesources and Geoenergy Engineering

Master Thesis

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Acknowledgements and Dedication

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I would like to thank and dedicate this thesis to my mom, Elizabeth Monroy, whose unwavering love, support and hard work has made me the man I am today. She is my role model, and I am blessed to have her as a mother, I love you mom, thank you for everything you have done for me. I am also grateful to my aunts, Ruth, Edith, Marisela, my uncle Edgar, my cousin Andrew, the rest of the Monroy family who have always been there for me, and a belated thank you for everything that they gave and did for me to my grandparents, Neftalí Monroy Ramírez, Victoria López Leyra, and María Dolores Elías Estrada.

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Abstract

This thesis discusses the security of gas supply in Italy and the European Union despite geopolitical conflicts currently taking place in the region. The current situation of the Italian and the European Union supply and production of natural gas is presented, as well as what are the issues that they are facing to guarantee this hydrocarbon to their citizens. The current situation of their respective energy infrastructures is also presented with explanations as to how they utilize natural gas to create products or as fuel to power turbines to generate electricity. Case studies are presented detailing what are the consequences when the gas supply security of a nation is compromised, be it because of geopolitical factors or natural disasters, and how cities and nations have taken measures to mitigate the respective risks. The use of early warning systems is discussed, how they work, why are they important, and how are they contributing to secure the energy supply of a country; at the same time, the use of artificial intelligence combined with machine learning models in these systems, how it is helping these systems, the development of its adoption, the improvement of these systems, and some models are presented. The findings highlight the importance of early warning systems that use artificial intelligence combined with machine learning models to guarantee the security of gas supply in Italy and the European Union.

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Introduction

Energy is a force that makes things move, it is not made or created, it transforms itself into different kinds of energy like heat, electrical, motion, gravitational, light, etc. One of the largest contributors to the energy sector is the oil and gas industry where fossil fuels are extracted from the underground to be converted into useful products for society and to be burned to harness the energy that is stored inside. However, the transformation and consumption of energy are not just technical processes; they are deeply intertwined with geopolitics and economic dynamics. Energy flows and supply chains create dependencies between nations, making the stability and security of energy resources a matter of international concern. This connection becomes evident when geopolitical tensions arise, impacting not only energy availability but also the economic resilience of entire regions.

Our societies are incredibly dependent on each other and what affects one nation, will most likely affect another one. This has been the case for some time due to the conflict between Russia and Ukraine. A substantial portion of Russian natural gas exports to the EU transits through Ukraine. The conflict has jeopardized the security and reliability of these pipelines, causing disruptions and concerns over potential damage or sabotage. Likewise, the EU has imposed economic sanctions on Russia, including measures targeting the energy sector. These sanctions have hindered the ability of European companies and governments to engage in energy transactions with Russian entities, complicating the import of natural gas. These are the answers to the question of how the conflict between Russia and Ukraine has affected the natural gas supply in the EU, and Italy.

Amongst different ongoing conflicts around the world, nations must assure a constant supply of energy to satisfy their national demand. However, it is impossible to predict when and where the next issue in this long supply chain will occur, but it is possible, by looking at their geopolitical relations as well as other information, to build systems that can identify situations that could lead to a disruption of the energy supply.

The thesis is made up of six chapters, with the first one exploring what is the current natural gas situation of Italy and the European Union is like; afterwards, the energy infrastructures of Italy and the EU are studied detailing the many uses of natural gas for them and how their facilities transform this source of energy into useful products for society; next the importance of having security in the gas supply of a country, where different examples of how this fossil fuel has affected geopolitical relationships between countries as well as how natural disasters can impact the energy supply of a nation; chapter four explores how governments have developed security measures to prevent an energy crisis from escalating, in this case, early warning systems are the main focus; chapter five explores the applications of artificial intelligence in early warning systems for different types of sectors; and the last chapter discusses the applications of artificial intelligence in early warning systems focusing on the energy sector.

Chapter I: Natural Gas in Italy and Europe

Italy and the European Union (EU) have always relied on imports of natural gas from other countries to satisfy their respective energy needs. However, this has made them vulnerable to fluctuations in the supply of natural gas, to factors that are out of their control.

In 2021, the main supplier of natural gas to Europe and Italy was the Russian Federation (close to 50% for the EU, and 38.2% for Italy). However, after the breakout of the war between Russia and Ukraine, the EU and Italy had to rely on other countries to fulfill their respective energy requirements. As of now, for Italy, the main supplier of natural gas is Algeria with almost 41% of the gas coming to the Italian Peninsula being from this country; as for the EU, the main supplier is now Norway with 30.3% and the United States of America with 19.4%.

As the conflict continues, only time will tell if the EU and Italy will go back to Russia being their supplier, or if their alternatives are better than what they had before the war.

Italy

The Russian Federation was the main supplier of natural gas to Italy. However, after their attack on Ukraine, Italy placed harsh sanctions towards the importation of Russian gas, which gave the opportunity for Algeria to take the spot of Russia as the main supplier of methane to Italy.

In 2021, the gas imports of Italy were comprised in the following way:

- Russia, 38.2%
- Algeria, 27.8%
- Azerbaijan, 9.5%
- Italy, 4.4%
- Libya, 4.2%
- Norway and the Netherlands, 2.9%
- Other, 13.1%

In 2023, the gas imports of Italy were comprised in the following way:

- Algeria, 37.4%
- Azerbaijan, 16.2%
- Norway and the Netherlands, 10.7%
- Russia, 4.7%
- Libya, 4.1%
- Other, 26.9%

“Other” refers to Liquefied Natural Gas.

How natural gas arrives in Italy

The natural gas coming from Russia is transported through the gas pipeline known as Brotherhood, which is one of the main Russian pipelines into Europe. This pipeline is connected to the Trans Austria Gas (TAG) pipeline which goes through Austria and makes its way to the Tarvisio Gas Facility in Friulia-Venezia Giulia.

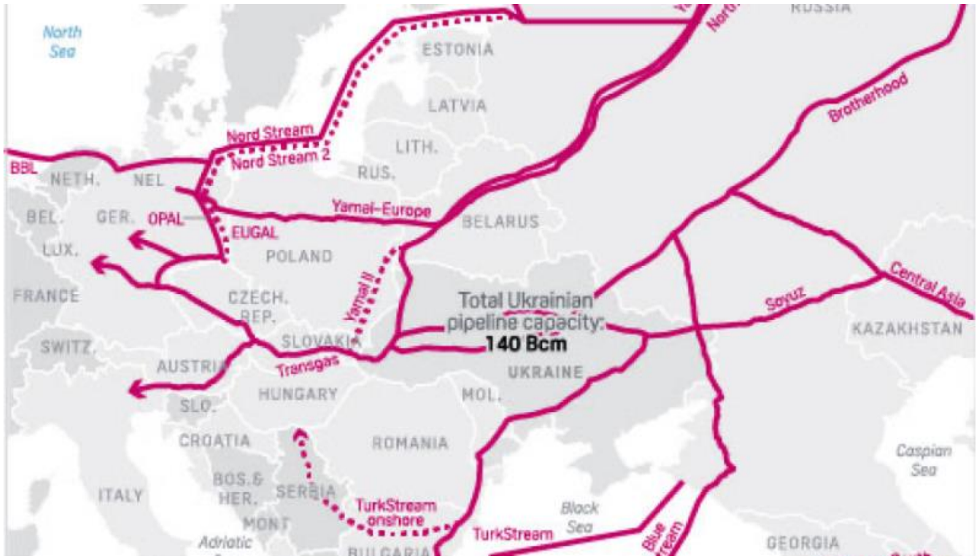

Figure 1.1: Main Russian pipelines[1]

For the gas coming from Northern Africa, the pipelines used are the following:

- Algeria, this country uses the Transmed pipeline, seen in purple on the map, the gas comes into the Mazara del Vallo facility in Sicily.
- Libya, the gas coming from here travels through the Greenstream pipeline, seen in green on the map, and it is received at the Gela facility, also in Sicily.

Figure 1.2: Main Northern African pipelines[2]

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[1] DeLay, J. (2022, May 24). Poland terminates Yamal pipeline agreement ahead of schedule. bne INTELLINEWS. https://www.intellinews.com/poland-terminates-yamal-pipeline-agreement-ahead-of-schedule-245351/

[2] Gandelli, S. (2022, February 24). Le vie del Gas naturale in Italia: il metano Russo e i principali gasdotti per l'import. Geopop. https://www.geopop.it/le-vie-del-gas-naturale-in-italia-il-metano-russo-e-i-principali-gasdotti-per-limport/

In the case of Azerbaijan, the pipelines used are the South Caucasus Pipeline (SCP), the Trans Anatolian Pipeline (TANAP), and the Trans Adriatic Pipeline (TAP) which unloads in Puglia.

Figure 1.3: Azerbaijan – Italy pipeline connection[3]

Lastly, for Norway and the Netherlands, the pipeline used is known as the Transitgas Pipeline.

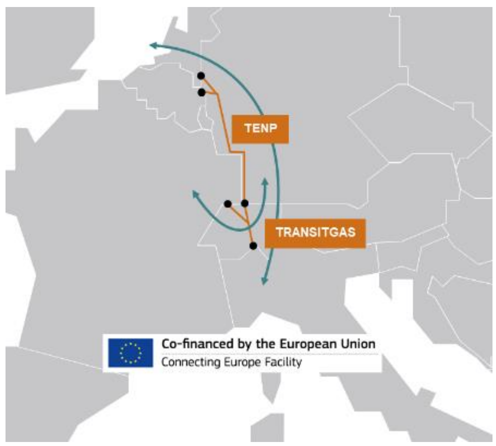

Figure 1.4: Transitgas Pipeline[4]

On February 10, 1953, the Italian Government along with Enrico Mattei put Italy on the petroleum world stage when they founded the Italian petroleum company Eni. Soon after its foundation, Eni started developing projects nationwide as well as outside of Italy. The Italian peninsula may not have the oil and gas reserves that Venezuela, Russia, the United States, Saudi Arabia, or other Arab countries might dispose of, but it does have a strong company that is internationally recognized as such. According to the Ministry of the Environment and Energy Security the proven, probable, and possible gas reserves for Italy in 2023 were 41.8, 37.062, and 17.746 billion standard m^3, respectively. The gas reserves of a country differ in the following way, a proven gas reserve refers to those quantities of petroleum which have been deemed to be commercially recoverable using the technology that is currently available; a probable gas reserve refers to those reservoirs which have a higher than or equal to 50% chance of being economically and technologically produced; lastly, a possible reserve is that which has a

[3] *Id.*
[4] Fluxys, (n.d.). *Transitgas Pipeline*. https://www.fluxys.com/en/about-us/fluxswiss/transitgas-pipeline

lower than 50% chance of being economically and technologically produced. The following table shows the estimated gas reserves for 2023.

GAS RESERVES (billions of Sm^3) as of 31/12/2023				
	Proved	Probable	Possible	% Certainty
Northern Italy	1.734	1.480	0	4.1%
Central Italy	412	196	41	1.0%
Southern Italy	23.976	23.831	15.990	57.4%
Sicily	1.149	432	233	2.7%
LAND Total	27.271	25.938	16.263	65.2%
Zone A	4.937	3.118	754	11.8%
Zone B	3.148	1.214	32	7.5%
Zone C+D+F+G	6.451	6.791	696	15.4%
MARINE Total	14.536	11.123	1.482	34,8%
TOTAL	41.807	37.062	17.746	100.0%

Table 1.1: Italian Gas Reserves[5]

To have a comparison of how much natural gas is consumed and produced in Italy on a yearly basis, in 2021 the production of gas in Italy was 3.5 billion standard m^3 and its consumption was 70 billion standard m^3, only 5% of the national consumption of natural gas was covered by domestic production. For 2023 the production of gas in Italy was 3.04 billion standard m^3 and its consumption was 61.5 billion standard m^3, 4.9% of the total consumption was provided by national production. Even though there was a reduction in the utilization of natural gas of nearly 10 billion standard m^3, the amount of gas supplied by Italian reservoirs was practically the same in terms of percentage. The region of Italy that extracts the largest amount of natural gas on land is Basilicata, followed by Sicily and Emilia Romagna. For offshore production Zone A is the one that leads the extraction of gas. This extraction information can be seen in the table below obtained from the Ministry of the Environment and Energy Security:

[5] Ministero dell'ambiente e della sicurezza energetica. (2023). *Riserve nazionali di idrocarburi. Anno 2023.* Ministero dell'ambiente e della sicurezza energetica. Direzione generale fonti energetiche e titoli abilitativi. https://unmig.mase.gov.it/ricerca-e-coltivazione-di-idrocarburi/riserve-nazionali-di-idrocarburi/

Ministero dell'ambiente e della sicurezza energetica - Direzione generale infrastrutture e sicurezza (IS) - Ufficio nazionale minerario per gli idrocarburi e le georisorse (UNMIG)

PRODUZIONE NAZIONALE DI IDROCARBURI - ANNO 2023

RIPARTIZIONE DELLA PRODUZIONE PER REGIONI E ZONE MARINE

Produzione di GAS NATURALE (Smc)													
	Gennaio	Febbraio	Marzo	Aprile	Maggio	Giugno	Luglio	Agosto	Settembre	Ottobre	Novembre	Dicembre	Totale
Abruzzo	617.382	753.721	1.153.449	817.869	1.097.869	1.114.736	1.134.741	1.121.324	1.134.265	868.858	1.135.854	1.207.670	12.157.738
Basilicata	109.050.575	91.214.440	96.890.929	91.294.973	89.040.813	81.288.788	89.498.371	90.084.621	91.897.890	96.331.478	92.723.462	92.839.636	1.112.155.976
Calabria	428.964	386.340	420.269	399.847	410.805	405.212	416.320	416.762	432.610	459.630	437.747	460.821	5.075.327
Emilia Romagna	10.389.146	9.503.009	10.101.584	9.780.654	10.134.250	8.904.247	11.111.176	9.701.708	9.808.833	10.000.412	9.596.231	10.268.376	119.299.626
Lombardia	1.385.171	1.195.766	2.226.066	1.819.115	1.828.381	1.735.263	1.941.035	1.975.401	1.756.629	2.059.766	1.813.576	2.032.556	21.768.725
Marche	226.199	380.220	557.847	62.885	383.120	449.897	521.899	523.638	506.375	556.692	501.060	544.715	5.214.547
Molise	4.265.647	3.794.235	4.350.151	4.201.531	4.393.160	3.648.779	2.965.136	4.128.109	4.013.789	4.123.151	3.972.127	4.396.116	48.251.931
Piemonte	551.414	537.740	634.445	613.105	613.066	594.597	478.601	444.058	567.089	332.255	0	0	5.366.370
Puglia	4.460.888	3.774.176	4.205.912	3.992.736	4.422.820	4.263.592	4.632.589	4.415.072	3.927.793	3.653.301	2.586.059	2.554.004	46.888.942
Sicilia	13.971.207	12.603.191	13.769.997	13.344.308	13.704.933	13.620.334	13.248.920	13.156.336	12.477.180	12.396.212	12.925.195	14.297.961	159.515.774
Toscana	227.012	86.199	244.962	218.347	190.916	159.791	127.737	117.744	161.835	138.794	159.805	188.033	2.021.175
Veneto	182.169	171.115	184.116	152.990	162.953	68.026	177.637	97.979	0	0	102.708	91.538	1.391.231
Totale Terra	145.755.774	124.400.152	134.739.727	126.698.360	126.383.086	116.253.262	126.254.162	126.182.752	126.684.288	130.920.549	125.953.824	128.881.426	1.539.107.362
Zona A	68.606.872	62.078.973	66.085.723	60.798.225	60.016.446	58.334.542	59.447.250	57.529.641	54.414.816	54.653.384	48.728.064	45.495.408	696.189.344
Zona B	44.848.398	39.794.132	43.719.885	41.445.198	42.914.169	40.731.597	41.894.981	41.021.013	39.124.645	39.674.247	38.449.519	39.156.868	492.774.652
Zona C	265.508	242.269	252.895	231.567	247.151	229.045	228.510	227.622	237.289	267.123	232.297	259.876	2.921.152
Zona D	23.756.760	20.286.964	22.058.009	21.665.110	24.642.477	25.103.137	26.312.186	29.217.437	29.103.672	29.972.103	27.904.103	29.422.435	309.444.393
Totale Mare	137.477.538	122.402.338	132.116.512	124.140.100	127.820.243	124.398.321	127.882.927	127.995.713	122.880.422	124.566.857	115.313.983	114.334.587	1.501.329.541
Totale	283.233.312	246.802.490	266.856.239	250.838.460	254.203.329	240.651.583	254.137.089	254.178.465	249.564.710	255.487.406	241.267.807	243.216.013	3.040.436.903

Figure 1.5: Italian National Hydrocarbon Production in 2023[6]

In the following map created by Progetto ViDEPI, all these marine zones are visible as well as all of the approximate 1,300 wells.

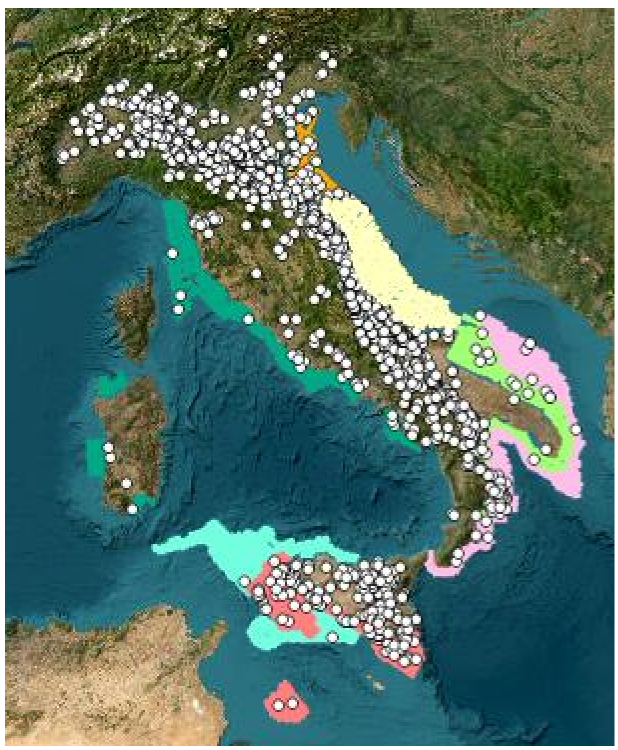

Figure 1.6: Wells and Marine Zones destined for gas extraction of Italy[7]

[6] Ministero dell'ambiente e della sicurezza energetica. (2023). *Produzione nazionali di idrocarburi. Anno 2023.* Ministero dell'ambiente e della sicurezza energetica. Direzione generale fonti energetiche e titoli abilitativi. https://unmig.mase.gov.it/ricerca-e-coltivazione-di-idrocarburi/produzione-nazionale-di-idrocarburi/

[7] Progetto ViDEPI - Visibilità dei dati afferenti all'attività di esplorazione petrolifera in Italia. (2024). https://www.arcgis.com/home/webmap/viewer.html?webmap=7596b9556827437b8b540d52bf3dbff4&extent=9.6927,41.1093,17.8061,44.7086

Of the nearly 1,300 gas wells drilled throughout Italy, almost 800 of them are not currently active, meaning that there is no hydrocarbon extraction coming from them, while the rest of them are active. Regarding offshore production, as it was stated previously, Zone A is the one that extracts the most amount of oil and gas, followed by Zone B, the Adriatic Sea is where most of the natural gas reservoirs are located. The different marine zones destined for gas extraction throughout the Italian coastline are detailed below:

- Zone A, highlighted in orange, covers the coasts of the regions of Veneto and Emilia-Romagna
- Zone B, highlighted in white, covers the coasts of the regions of Marche, Abruzzo, Molise and the northern coast of Puglia
- Zone C, highlighted in red, covers the southern coast of the island of Sicily while also covering the island of Faraglione di Tracino in the Mediterranean Sea
- Zone D, highlighted in green, covers the entire coast of the regions of Puglia, Basilicata, and a small part of the coast of Calabria
- Zone E, highlighted in turquoise, covers the whole coasts of the regions of Toscana, Lazio, as well as the small gulf under the peninsula in the region of Campania
- Zone F, highlighted in pink, covers the entire coast of the region of Calabria, and the deep waters around the coast of Puglia.
- Zone G, highlighted in sky blue, covers the western deep waters off the coast of Sicily, as well as a section of the northern coast of this island

It is important to mention the fact that even though zone A is the one that produces the largest amount of natural gas, it is not being produced to its full potential because of the Italian legislation to protect the city of Venice. Article 8 of the legislation passed on August 6th, 2008 n. 133 forbids the exploration, research, and extraction of hydrocarbons in the waters of the Gulf of Venice, this is because the Italian Government is protecting the city of Venice from further sinking. This city is a protected UNESCO World Heritage Site and therefore laws has been passed to preserve the city for as long as possible, at the same time this city is famous worldwide and it brings in much needed revenue to its inhabitants and the region, so it is in the best interests of the Italian nation to preserve it for as long as possible. Policymakers believe that the continuous extraction of natural gas from the reservoirs located in this area will further contribute to the sinking of the city. During the 1970s water was being pumped out from the aquifers below Venice which did lead to a significant subsidence, this is one of the main reasons why politicians are hesitant to develop this zone to its full potential. However, some experts reject the idea that hydrocarbon extraction will lead to a further sinking of the city; these engineers argue that the reservoirs are located far away from the city, and that they are also small in comparison to others, this in turn would not contribute to the possible subsidence of the city generated from the extraction of hydrocarbons.

In 2017, the Energy Information Administration (EIA) of the United States made the following observations on the position of Italy in the European natural gas stage, highlighting the imports made as well as the national production:

> *"Italy is the second-largest natural gas importer in Europe after Germany, and the third-largest consumer of natural gas after Germany and the United Kingdom. Natural gas imports were 2.3 trillion cubic feet (Tcf) in 2016, and dry natural gas production that year was 0.2 Tcf. Natural gas imports accounted for about 92% of the total natural gas supply in Italy."*[8]

It is evident that the national production of gas is not enough to cover the demand of Italians and most of the gas consumed in Italy is imported. As of 2024, the main suppliers of natural gas to Italy are the countries of Qatar, the United States, and Algeria.

Europe

Similar to the sanctions imposed by Italy, Russia used to be the main supplier of natural gas to the European Union, but this all changed after they attacked Ukraine. In 2021, 50% of all the natural gas that was being used in Europe was imported from Russia. In 2023, most of the supply of this fossil fuel came from Norway followed by the United States. The percentages are presented in the following list:

- Norway, 30.3%
- United States, 19.4%
- Northern Africa, 14.1%
- Other, 10.3%
- Russia, 8.7%
- Russian LNG, 6.1%
- UK, 5.7%
- Qatar, 5.3%

It is important to highlight the fact that in 2023, US imports of LNG were approximately 50%. These imports tripled when compared to data from 2021, making the US the largest supplier of LNG to the EU during that year.

Gas is a vital energy source for many countries, especially in Europe, where it accounts for a significant portion of electricity generation and is essential for heating and industrial processes. Disruptions in gas supply can lead to increased energy prices, which can have cascading effects on the economy, affecting everything from manufacturing costs to consumer prices. In the EU, gas is the marginal supplier in the electricity mix, meaning that fluctuations in gas availability can directly impact electricity prices and reliability.

The geopolitical landscape significantly influences gas supply security. For instance, reliance on a single supplier can expose nations to risks associated with political instability or conflicts involving that supplier. The recent crisis stemming from Russia's invasion of Ukraine highlighted the vulnerabilities in European energy security, as many countries were heavily dependent on Russian gas. This situation prompted a reevaluation of energy policies

[8] U.S. Energy Information Administration. (2017, August). https://www.eia.gov/international/analysis/country/ITA

across Europe, emphasizing the need for diversification of supply sources and increased resilience against geopolitical threats.

Looking at all of Europe, just as it was with Italy, the European Union (EU) relies heavily on natural gas imports to meet its energy demand. This dependence of the EU on natural gas exports from third countries is mostly due to a decline in the domestic production, the current transition of energy, geopolitical factors, such as the war between Russia and Ukraine, and a lack of an investment in energy infrastructures.

In recent years, the natural gas production in the EU has decreased significantly, from 2020 to 2023 the extraction declined by approximately one third, this was due to a large cut coming from the Netherlands since they decided to phase out all production coming from a field located in Groningen, they expect to cease all production from here by the end of 2024. Historically, the Netherlands has been the largest producer of natural gas of the EU. The decline of gas production inside the EU is expected to drop even further due to the depletion of reservoirs that are in their last stage of production, which in turn increases the dependence of the EU on imports from other countries.

Even though the members countries of the EU are transitioning to renewable energy sources, and an amount of energy produced by them is covering the demand, the amount of energy generated from natural gas is a lot higher than that generated from renewable energy sources. This difference in quantity of energy generated from natural gas and renewables is mainly due to the reliability, efficiency, infrastructure, availability and the cost effectiveness of natural gas.

Natural gas power plants are highly reliable, electricity generation can be quickly ramped up or down to meet the demand, this flexibility allows them to provide electricity during peak demand periods, such as hot summer days when air conditioning use increases or during cold winter nights when people want to warm their houses; these plants are also efficient when it comes to converting fuel into electricity, they can achieve efficiencies of 50 up to 60%, especially if they are using a combined cycle setup. Another thing to consider is the fact that natural gas is widely available and can be easily transported through an extensive network of pipelines. It can also be stored for long periods of time in underground facilities, allowing for energy to be dispatched as needed. This infrastructure supports a stable supply, which is essential for meeting continuous electricity demand. Lastly, since there is a large amount of gas in the world, this makes it more affordable than electricity generated from other sources, making it an attractive option for consumers and utilities, its cost has generally been lower than that of other energy sources, contributing to its widespread adoption in electricity generation. Natural gas remains a significant source of electricity generation in the EU, but its share is decreasing as renewable sources like wind and solar are rapidly increasing their contributions. The commitment of the EU to reduce their dependence on fossil fuels and its increase in renewable energy capacity is evident in these trends, with natural gas serving as a transitional energy source to support the integration of renewable energy sources to the grid.

The Russian invasion of Ukraine and the subsequent reduction of Russian gas imports have highlighted the need for diversification of energy sources as well as the need to increase the import of natural gas from other countries, it is important to mention the fact that before Russia attacked Ukraine, the Russian Federation was the largest supplier of natural gas to the EU. In order to achieve this diversification of gas supplies, a significant investment in infrastructure, such as new pipelines and liquefied natural gas terminals, is needed.

The member countries of the EU that import the highest amount of natural gas into their territories are Germany, Italy, France, Spain, and Belgium; the reason why are main importers of this energy source is because these countries are the ones that consume the most amount of it. Given the fact that the EU is not able to satisfy its energy needs and relies heavily on imports, the countries from which they import the most amount of gas are Norway, the United States, Algeria, the United Kingdom, and Qatar; this ranking has changed dramatically due to the ongoing conflict in Ukraine, highlighted by Łoskot-Strachota, Keliauskaitė, and Zachmann (2024):

> *"Between 2020 and 2023, the share of Russian gas in EU gas imports dropped from around half to 15 percent. Norway is now the main external gas supplier to the EU, delivering most of its gas via pipelines. Liquified natural gas (LNG) from the United States now competes with Russian gas for second place on the EU market. New sources including Egypt, Angola and Oman and increasing imports from Azerbaijan have made the EU gas import mix more diversified."*[9]

Even though the EU is fulfilling its demand for natural gas by a mix of domestic production and imports, they are still in a tight situation where measures have to be taken into place to avoid any gas shortages. One of these measures consists of increasing the rate at which improvements on energy efficiency are made in residential buildings, electrical appliances, and lighting. People occasionally forget to turn off the lights before heading out, or leave something plugged in, these actions consume energy and perhaps it might not be reflected on their electrical bill, leading to consumer indifference. However, if this case is scaled up, there is a significant amount of wasted energy, the power grids of a city might be able to handle this, but electricity is still being used without any benefit. Consumers need to make sure that once they leave their home, all of their items that use electricity are disconnected from the sockets, and that the lights are turned off; this small improvement from every citizen contributes to this measure. Cities also have a role to play when it comes to public lighting, people feel safe when they have the ability to see, it lets them react accordingly, if a park, a street or an alleyway is dimly lit at night people will stay away from it because they are not able to see. Public lighting is a double-edged sword, cities for

[9] Łoskot-Strachota, A., Keliauskaitė, U., Zachmann, G. (2024, July, 3) *Future European Union gas imports: balancing different objectives*. Bruegel. Publications. Analysis. https://www.bruegel.org/analysis/future-european-union-gas-imports-balancing-different-objectives

many years have figured out when to turn on and off city lights, but now there are more efficient ways of illuminating the streets, from light bulbs to LED lights, cities have started transitioning to these since they are more efficient and have a larger area coverage, this could in turn lead to less light posts and therefore less energy being required to light a city.

Another measure, which also contributes to the reduction of CO_2 emissions and the energy transition aside from preventing gas shortages, is a faster deployment and adoption of renewable energy resources. On a small scale, as it can already be seen in many countries of the EU, households have solar panels that generate energy for them which also reduces their electric bill; consumers know that there are many benefits when it comes to implementing renewables in their homes, however sometimes the barriers of entry are too high for them because to start out with this kind of technology, changes have to be made to their homes so that they can connect to the electricity grid, this means that they will have to spend money on this, and consumers could not see a possible long term benefit of adopting renewables. It is here where governments have to step in to grant concessions for families that want to implement this kind of technology and aid them. On the other hand, the companies that will provide the service would also like to see an economical benefit from this, because changes will always be made as long as there is money to be made, or saved, from an opportunity. Governments are the ones who have to balance out the requirements and wishes of both parties to reach an agreement to fully implement this measure.

Another point to consider to avoid shortages is the need to electrify heat. The reason why the EU is reliant on natural gas is because winters in the majority of the member countries of the union are harsh and cold, with Finland, Estonia, Latvia, Lithuania, Sweden, Poland, Austria, Slovakia, Czechia, and Germany being the ones that are hit the hardest during this time. Many of these countries have natural gas boilers that are used constantly during the cold months, this in turn leads to a large amount of gas required for them to work. A way in which boilers could be phased out would be by replacing them with electrical heat pumps, however, just as it was with the adoption of renewable energies, people will go with the most affordable option for them and it is up to each country to aid their citizens by either providing incentives for families to purchase these pumps, changing tax measures to promote electrification and get the manufacturers involved so that they can see a benefit as well and promote industrial electrification.

Finally, the last measure to avoid gas shortages involves the cooperation between governmental environmental agencies and oil and gas companies, it consists of increasing the supply of gas available. For the longest time as an oil reservoir began production, companies would focus mainly on the extraction of crude oil since, gas was not seen as profitable as oil was and since no one was buying it, companies would often vent it into the atmosphere, this heavily contributed to climate change, the greenhouse gas effect in the atmosphere, and the hole in the ozone layer. During the 1980s researchers and policymakers started taking actions towards to reduce the hole in the ozone layer after British scientists discovered its formation on top of Antarctica in 1985 and in 1987 the Montreal Protocol was signed which led to the healing of this layer. Since venting the gas was not allowed anymore, companies started burning it, generating CO_2, this was done because there was no one was buying natural gas as much, but a company will never stop producing, and therefore the least harmful solution was to burn it. Nowadays, gas shortages could be mitigated by simply capturing all of this gas that is extracted from oil fields. After the capture of the gas, it has to be stored, so an investment to increase the storage capacity has to be done; this gas could also be reinjected into depleted reservoirs and extracted once it is needed, this needs to be scaled up as it is already being done worldwide.

The natural gas panorama for the EU and Italy is similar. Italy has gas reservoirs located within its borders, and it is producing them, the Adriatic Sea as well as the region of Basilicata are the ones that produce the most amount of gas. However, most of the reservoirs within its borders are composed of many thin layers, because of this the production interval of the well is not the most efficient since it is not extracting hydrocarbons from all of the layers, this could in turn lead to production coming from only some layers, abandoning the interval, going up the well, detonate the desired interval and begin production, this is not an efficient extraction method. Usually, reservoirs have a single production interval where they can extract the most amount of oil before the production parameters are changed according to a previously established technology. Another fact to consider is the oil and gas extraction legislation, as it was mentioned, one of the areas where there is a large amount of natural gas cannot be fully developed due to laws protecting Italian cities and the environment. It is for this reason that almost 95% of all of the gas used in Italy is imported from other countries.

The countries that make up the European Union have never been known for the extraction of oil and gas in the European continent, even though they have strong companies like Repsol for Spain, Total Energies for France, bp for the UK, Shell for the Netherlands and the UK, and of course, Eni for Italy; however, these same countries, along with the rest of the EU, have been reliant on imports coming from outside the EU for the longest time. Russia used to be the largest supplier of gas, but after the events that took place on February of 2022 the EU adopted different strategies to cut Russian gas imports, and there is a wish to fully stop their reliance on the gas coming from Russia. Many strategies have been developed and adopted, Norway, the United States, Algeria, Qatar have become the main suppliers of gas to the European continent; the push for renewable energy resources and increasing the capacity and efficiency of these technologies, as well as the availability for their populations to adopt them and see the economic and environmental benefits that can come from using them. This must be developed in an intelligent manner, considering the requirements of the end user, the priorities of the manufacturers, and a deep understanding of the energy systems and a natural gas supply security.

Chapter II: Energy Infrastructures

As it was detailed in the previous chapter, natural gas is a crucial resource for Italy and the EU since it is used to satisfy a significant portion of their energy needs, this in turn makes reliable infrastructures key for maintaining stable energy supplies. It also substantially contributes to many national economic sectors, fostering the creation of jobs and driving technological innovation. At the same time, trading and marketing of this fossil fuel influences international relations and energy policies. Lastly, this gas is seen as a step towards the transition to renewable energies, even though it is a hydrocarbon itself, but the carbon footprint left by it after it has been burned is a lot less significant than that of oil. With this in mind, for societies to be able to make the most out of it, infrastructures have to be developed, with installations spanning from the technology and facilities required for its extraction, pipelines and ships for its transport, plants used for treating it, to the infrastructures needed for end users to be able to use it.

In general terms, an energy infrastructure refers to the physical and organizational systems required to produce, distribute, and consume energy in a given area. Energy infrastructures include:

- Generation facilities: Power plants, renewable energy installations (like solar panels, or wind turbines), and other sources of energy production.
- Fuel supply chains: Pipelines, storage tanks, and transportation systems for fossil fuels.
- Storage facilities: Batteries, and other means of storing energy for later use.
- Transmission networks: High-voltage power lines and substations that transport electricity over long distances.
- Distribution systems: Lower-voltage power lines, transformers, and meters that deliver electricity to the consumers.
- Control systems: Management and monitoring technologies to ensure efficient and reliable energy delivery.

In terms of natural gas there are two paths that must be considered, following the previous list. The first path, production path, begins with the extraction of the natural gas from the reservoir, this gas is then transported via pipelines to the gas processing facility where it reaches the end of this first track. The second path starts within the gas processing facility, where after the gas has been cleaned, it is transported to the end consumers through pipelines. For power generating purposes, electric companies burn the gas producing electricity; this electrical energy is then sent through power lines to substations, where it will be sent to smaller distribution centers to be further distributed until it reaches the end consumer.

The first path used by natural gas is depicted in the schematic below:

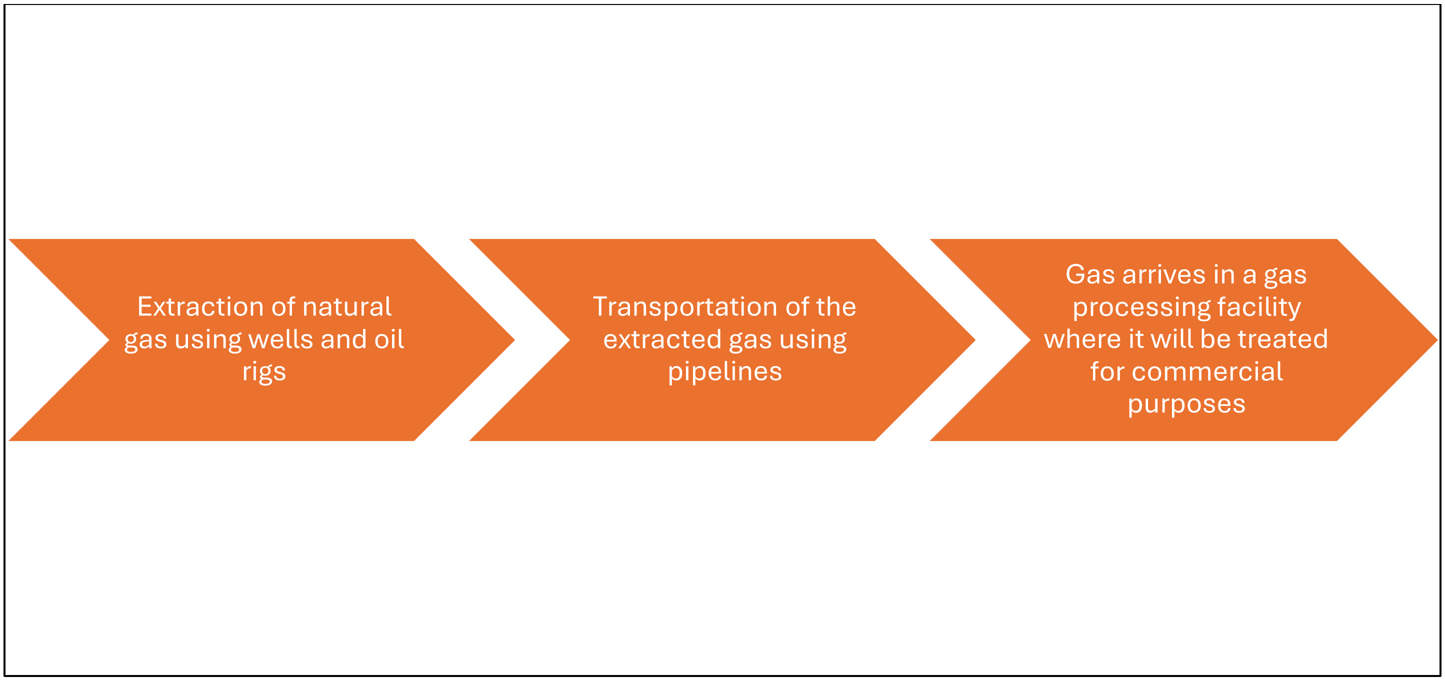

Figure 2.1: Gas extraction, transportation, and processing schematic

The energy infrastructures pertaining to the first path of the cycle described for natural gas begin with the extraction of this fossil fuel.

The first step can begin after geoscientists have determined that there is sufficient geological evidence that a geographical area contains hydrocarbons below. The service company will then begin the installation of the required infrastructure to develop the reservoir, after the drilling equipment and technology has been set up and drilling operations can begin, the go ahead is given to start. The well is then drilled and cemented according to the development plan, until it reaches the desired depth. Once the well is complete an explosive charge is lowered to the defined production interval, after confirmation has been given that it is correctly placed, it is detonated, and production of the reservoir can finally begin. The gas begins to flow from the reservoir up to the wellhead where the second step begins.

After the gas has traveled all the way to the top of the well, according to the configuration of the valves on the wellhead, the gas flows into pipelines which connect it to a main one where it will continue its journey until it reaches the gas processing facility, finishing the second stage on this path.

The third and final infrastructure where gas arrives at, in this first path, is the gas processing facility. It is here where the gas will be cleaned from its impurities as well as contaminants that come along with it, like CO_2 and H_2S. This process is essential to ensure that the gas meets the standards of quality required for safe transportation and use. The stages through which the natural gas has to go through to be removed from its impurities is the following:

1. *Separation of Liquids and Solids*, oil and water are removed using a separator whereby use of gravity the gas flows through the top while the liquids flow through the bottom.
2. *Dehydration*, the gas is dehydrated to remove water vapor by using different absorption and adsorption techniques. This is done because the vapor could lead to hydrate formation and pipeline corrosion.
3. *Contaminant Removal*, H_2S and CO_2 are removed via amine absorption to prevent pipeline corrosion and to make sure that the gas meets safety and quality standards.
4. *Mercury and Nitrogen Removal,* activated carbon beds are employed to remove traces of mercury if present. Nitrogen is a non-flammable gas, this reduces the calorific value of natural gas, therefore processes like cryogenic distillation are used to remove it from the gas mixture.
5. *Natural Gas Liquids Recovery,* through cooling and compressing processes, butane, ethane, and propane, are collected. The processes make them condense, removing them from the gas stream.
6. *Fractionation,* here butane, ethane, and propane are separated into individual components by using debutanizers, deethanizers, and depropanizers.
7. *Final Treatment,* here the gas is conditioned to meet the pipeline requirements. It is at this stage where mercaptan, an odorant, is added to the gas to give it the smell of rotten eggs, this is done for safety purposes, since natural gas does not smell of anything.

The processing of natural gas is a complex but crucial operation that transforms raw gas into a clean, usable fuel. Each stage of the process is key ensuring that the final product is safe and meets the required quality standards.

This entire process is explained in detail in the following figure obtained from the study made by Dr. Semih Eser on Natural Gas Processing:

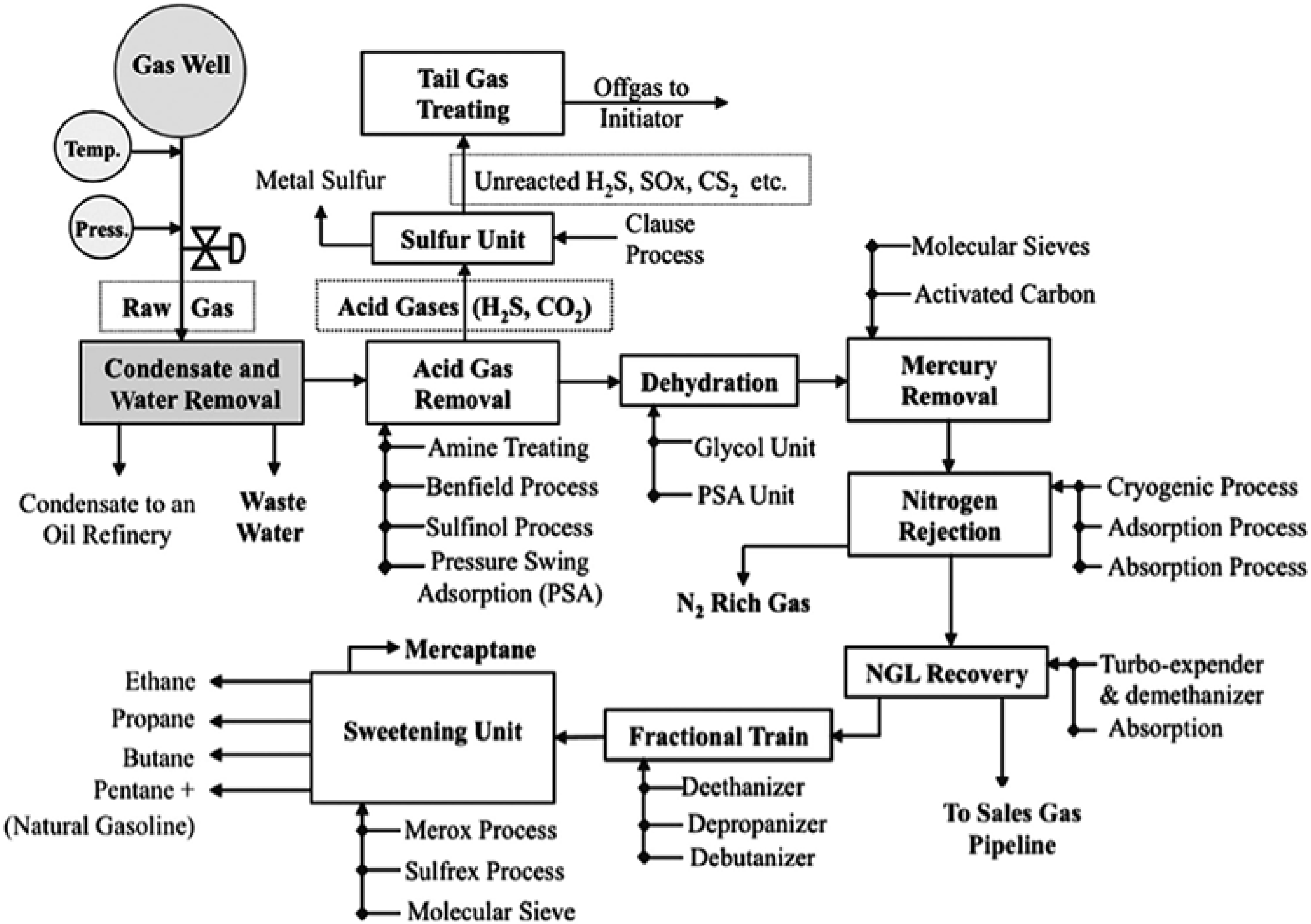

Figure 2.2: A generalized natural gas processing flow diagram[10]

As previously mentioned, the second path begins at the gas processing facility The second path starts within the gas processing facility after the gas has been cleaned, conditioned, and has been deemed to be ready for further distribution it is then sent to a natural gas company who will distribute it all users, including electric power plants, where it will be converted into electricity..

The second path used by natural gas is depicted in the schematic below:

[10] Eser, S. PhD. (N/A). *Natural Gas Processing*. College of Earth and Mineral Sciences, Penn State. https://www.e-education.psu.edu/fsc432/content/natural-gas-processing

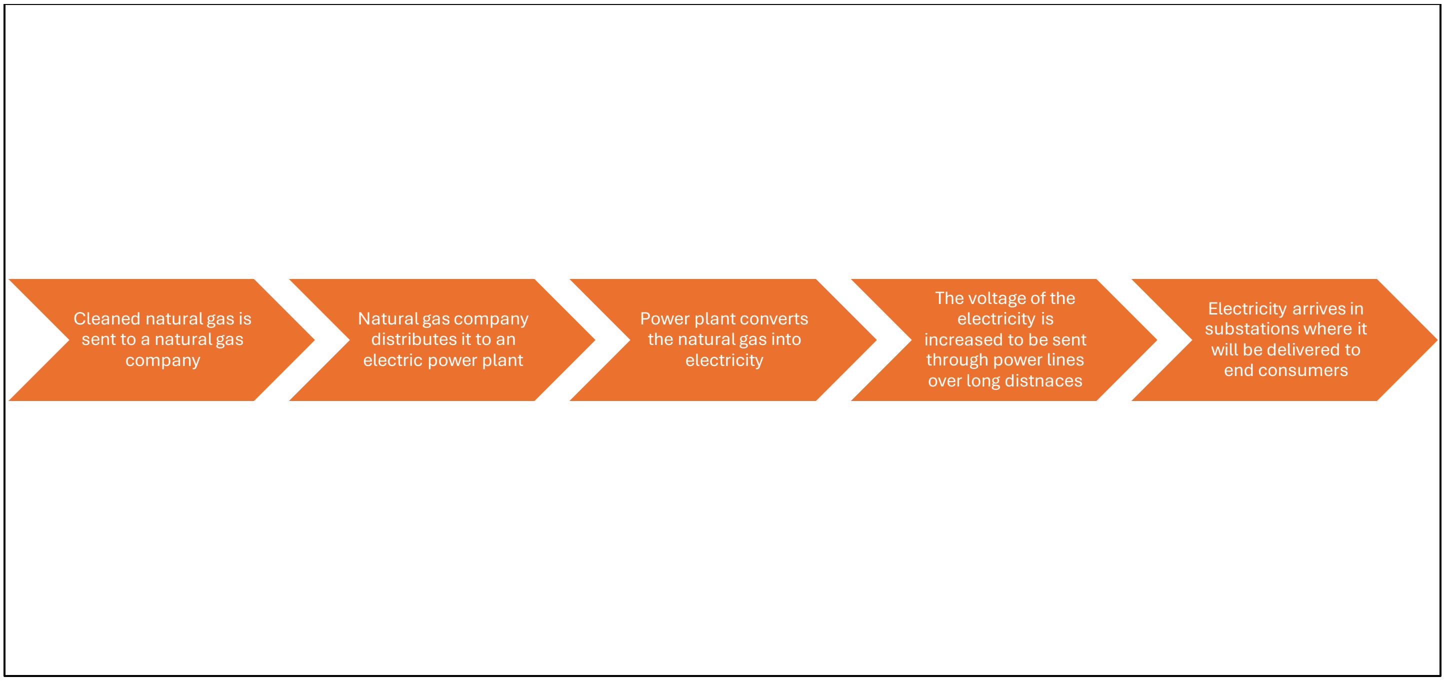

Figure 2.3: Illustration of the second path followed by natural gas to be converted into electricity and its distribution

MET Group (2023) described the process of generating electricity from natural gas in the following way, highlighting combustion, turbine operation, electromagnetic induction, transmission, and distribution:

1. *"Combustion,* the gas is burned in a combustion turbine and the heat generated from this thermodynamic process is used to move the turbine.
2. *Turbine Operation*, the turbine is connected to a generator and as the blades of the turbine spin, making the rotor of the generator turn, this creates an electromagnetic field.
3. *Electromagnetic Induction,* the spinning rotor within the electromagnetic field of the generator creates an electrical current through a phenomenon known as electromagnetic induction. This current is the electricity that is being produced.
4. *Transmission,* since the voltage of the generated electricity is not high enough to be sent across long distances, it is sent through power lines and transformers to increase the voltage.
5. *Distribution,* the electricity that was sent through the power lines is then distributed to substations which will distribute it to homes, businesses, and other end users by using local power grids. "

The entire process has to be monitored using meters and panels to ensure a successful, efficient and reliable energy delivery. If there is an energy surplus, it is stored using batteries or other power grids ready to be distributed amongst the consumers when required. However, this entire process also has to be closely monitored to prevent power surges, equipment malfunctions, which could in turn knock out the instruments for a long period of time.

An overview of the entire process of how natural gas is converted into electricity is detailed in the following figure obtained from the U.S. Energy Information Administration:

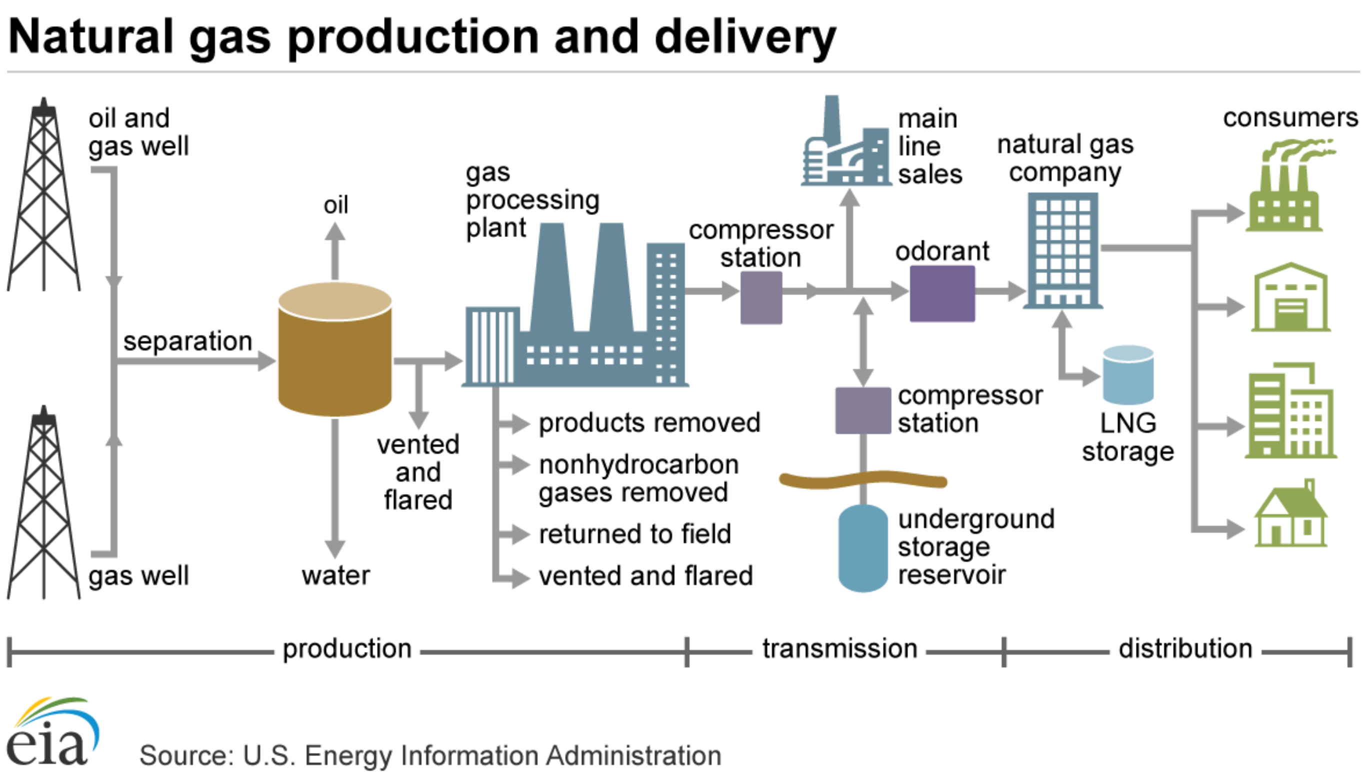

Figure 2.4: Natural gas production and delivery[11]

Another example of how natural gas is used is seen in the petrochemical industry, where it is used as feedstock for the production of different items and chemicals like synthetic fibers, solvents, dyes, adhesives, polyethylene, among others. At the same time, it is also used to power and provide the necessary heat for the petrochemical facilities that are being used to create these previous products. Natural gas is a versatile and vital component in the petrochemical industry, serving as both a raw material for chemical production and a fuel source for manufacturing processes. Its use has significant implications for the economics and the environmental footprint of the industry.

Natural gas is an essential raw material for producing ethylene, propylene, methanol, and hydrogen.

[11] U.S. Energy Information Administration. (2022, December, 27). *Natural gas explained.* Energy explained. https://www.eia.gov/energyexplained/natural-gas/

Ethylene and Propylene

Ethane and propane, which are natural gas liquids, are extracted from natural gas and are subsequently used as feedstocks in steam crackers to produce ethylene and propylene, which are the building blocks for many plastics, paints, fertilizers, and other petrochemicals.

Methanol

Methane is a gas at normal temperature and pressure (and is therefore not found in liquid form), and therefore cannot be used as ethane and propane are used. Methanol is produced using natural gas (with methane as its main component: typically about 87% by volume) as the main feedstock, and it is primarily produced through the catalytic conversion of a synthesis gas (syngas), which is a mixture of hydrogen, carbon monoxide, and sometimes carbon dioxide in very small quantities. A secondary production process is by biosynthesis of methane with enzymes as catalysts. The production process from synthesis gas generally involves three main stages:

1. Syngas Production: It can be produced using natural gas as the main feedstock through two methods: Steam Methane Reforming (SMR) and Autothermal Reforming (ATR).
   In SMR, the natural gas reacts with steam at temperatures ranging from 700 to 900°C in the presence of a catalyst which are usually mixtures of copper, zinc oxide, and alumina, to produce hydrogen and carbon monoxide.
   In ATR, the natural gas is partially oxidized with oxygen to generate heat and syngas at the same time.
2. Syngas Conversion to Crude Methanol: After syngas has been produced, it is converted into methanol in a reactor at high pressures, typically 50 to 100 bar, and moderate temperatures, from 200 to 300°C.
3. Crude Methanol Purification: Since the methanol has certain impurities, like water and unreacted gases inside of it, these must be removed. Firstly, the methanol, which leaves the second step in vapor phase, is cooled which leads to condensation. Afterwards, the condensed methanol is distilled to eliminate the gases and the water, until it reaches the desired level of purity; this distillation step includes several distillation columns to effectively remove all impurities.

Methanol, just as ethylene and propylene, is a cornerstone for many plastics, paints, fertilizers, among other petrochemical products.

Hydrogen Production

Natural gas is the primary raw material used to produce hydrogen in refineries using one of the methods used to produce syngas in the production of methanol, steam methane reforming. The process is similar to the one used for syngas generation. Methane from natural gas reacts with steam at high temperatures and pressures in the presence of a nickel catalyst to produce syngas. In this case, the syngas is a mixture of hydrogen, carbon monoxide, and carbon dioxide; whilst, for the generation of methanol, carbon dioxide was not present in the syngas. Lastly, additional hydrogen is generated through the water-gas shift reaction.

One thing to highlight as another use for natural gas in the generation of hydrogen, is that although it is being used as the primary feedstock, it is also being burned to provide the high temperatures required for the endothermic steam reforming reaction. This makes natural gas an economical choice for hydrogen production, especially in regions with abundant supplies, while also making it a flexible resource as it allows refineries to adjust hydrogen production based on demand and feedstock availability. Excess hydrogen produced can be used in various refinery processes, such as hydrotreatment and hydrocracking. From an environmental perspective natural gas generally has a lower carbon footprint compared to other fossil fuels, resulting in fewer pollutants and particulate matter emissions, and it can reduce emissions even further through the installation of carbon capture technologies. Nevertheless, methane is an important greenhouse gas, responsible for around 30% of the rise of global temperatures since the industrial revolution. Methane has a global warming potential (GWP) of 82.5 over a 20-year period – that is, a leak of one ton of methane is equivalent to emitting 82.5 tons of carbon dioxide.

As the industry moves towards cleaner energy solutions, there are ongoing developments in hydrogen production from natural gas:

- Blue hydrogen production, which combines natural gas reforming with carbon capture and storage, is being explored as a lower-emission alternative.
- Europe is focusing more on green hydrogen production using renewable electricity, which may impact the long-term role of natural gas in hydrogen generation.

Natural gas currently plays a vital role in refinery hydrogen generation units, serving as both the primary feedstock and an important fuel source. However, its future use may evolve as industries adapt to changing environmental regulations and explore alternative hydrogen production methods. Hydrogen is a crucial component in many chemical processes and is used to produce ammonia for fertilizers.

The following image is a list made by the U.S. Department of Energy compiling some of the products that are manufactured from natural gas.

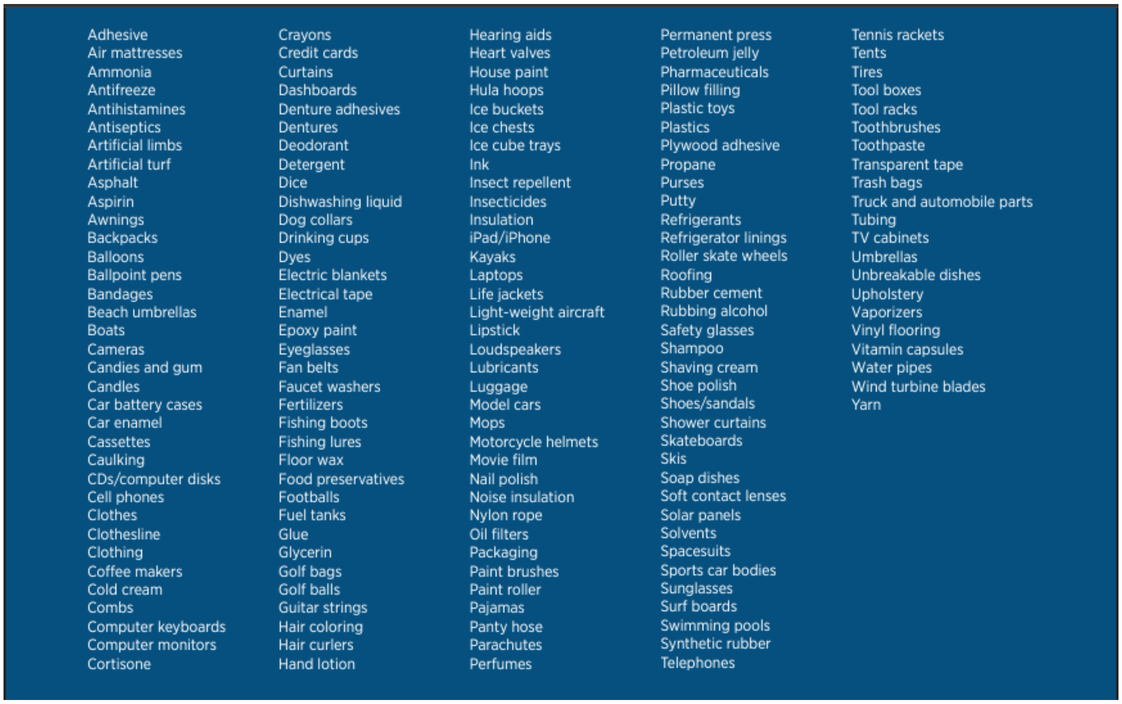

Figure 2.5: Products manufactured from natural gas[12]

Another aspect to consider is the fact that in regions where natural gas is abundant, like Russia and North America after the shale boom, this surplus has led to significant investments made towards the expansion of petrochemical capacities, giving these manufacturers a competitive advantage over international competitors, it is also important to consider the fact that natural gas prices have generally been more stable compared to oil prices, allowing for better long-term planning and cost management. This has reshaped the global petrochemical industry landscape, with many new projects being developed to capitalize on the advantageous feedstock situation.

When it comes to heat generation, natural gas is widely used for this purpose in both industrial and residential settings due to its efficiency and relatively clean-burning properties, as discussed previously. In industrial applications, natural gas is used in furnaces, ovens, and boilers to provide heat for manufacturing processes or to generate steam for other uses. This includes applications in:

- Metal production and fabrication
- Chemical manufacturing
- Food processing
- Paper production

In many industrial facilities that require the use of steam, boilers that use natural gas are utilized to generate it which is then used for:

- Powering turbines for electricity generation

[12] U.S. Department of Energy. (n.d.). *Products made from oil and natural gas.* U.S. Department of Energy. Infographic.

- Providing heat for industrial processes
- Sterilization in food and pharmaceutical industries

Also, the glass manufacturing and ceramic production industries use natural gas for direct flame heating to create their products.

On a residential scale, natural gas is primarily used for:

- Space Heating: Natural gas furnaces and boilers are common in homes, providing central heating by warming air or water that is then circulated throughout the house. This is especially done during the winter or in places that have cold temperatures year-round.
- Water Heating: Gas-fired water heaters are efficient for providing hot water for household use.
- Cooking: Even though some houses, especially in first-world countries, are switching from traditional gas-fired stoves to induction ones, many homes around the world still use natural gas stoves and ovens for cooking.
- Clothes Drying: Some households have natural gas-powered clothes dryers.

Natural gas heating systems have generally some advantages over electric heating systems (e.g. firing up and producing heat quickly on demand), especially in industrial applications, but they are less energy efficient and have shorter life spans. In both industrial and residential settings, modern natural gas heating equipment is designed to maximize heat output while using the least amount of fuel possible, making them as efficient as possible. The decarbonization in place for mitigating climate change demands the electrification of most heating systems. Nevertheless, these changes will take time, and natural gas will play a significant role in heating until 2050.

The scale of natural gas use varies significantly between industrial and residential applications. As expected, industrial facilities typically consume much larger volumes of natural gas, often using specialized equipment designed for heating at a high capacity. On the other hand, residential systems, while much smaller in scale, are designed for reliability and ease of use in home environments.

When comparing natural gas to other fuels for heating in terms of efficiency and cost, it has many advantages, although this depends on several factors. Modern natural gas furnaces and boilers can achieve efficiency ratings from 78% to 98%, which is higher than the typical efficiency of oil-fired boilers, which is around 85 to 90%. Regarding the cost, it depends on the relative prices of electricity, natural gas, and heating oil in the different markets. Natural gas is often one of the most cost-effective heating fuels, since it has been cheaper than heating oil. Another aspect to consider is the fact that the price of gas often drives electricity prices, as gas-fired power plants, since they are the largest consumers of natural gas, have frequently been setting electricity prices, so when electricity prices rise due to high gas prices, it can make natural gas heating relatively more attractive, because consumers are more likely to choose or keep their gas heating systems when faced with high electricity costs. This market situation might change with the wide dissemination of renewable electricity sources, like photovoltaic and wind turbines. Then, as industrial heating accounts for approximately 70% of total industrial energy consumption, and a gas oven is typically around 20 % more expensive than an electric one, it is foreseeable that natural gas heating systems will be replaced by electric ones.

Regarding the environmental impact of natural gas, Arthur East (2023), compared the emissions emitted by different fossil fuels and stated the following:

> *"In relation to the energy they produce when burned, different fuels emit different amounts of carbon dioxide (CO_2). To examine them, we compare the amount of carbon dioxide produced per heat content across different types of fuel. Here are the current carbon emissions from various heating systems:*
>
> - *Ground source heat pump (400%): 64 grams CO2 per kWh delivered heat.*
> - *Air source heat pump (320%): 80 grams CO2 per kWh delivered heat.*
> - *Direct electric heating (100%): 256 grams CO2 per kWh delivered heat.*
> - *Gas boiler (85%): 215 grams CO2 per kWh delivered heat.*
> - *Oil boiler (85%): 320 grams CO2 per kWh delivered heat.*
> - *Coal (50%): 630 grams CO2 per kWh delivered heat."*[13]

In addition to CO_2, gas heaters emit methane, nitrogen dioxide, carbon monoxide and formaldehyde, making them detrimental to the environment and human health.

Energy infrastructures are managed by many companies, as was explained in the previous processes, one company is in charge of the extraction and pipeline distribution, another company in charge of the treatment of the gas, while another will take the gas and will convert it to electricity that will then be distributed to different users. It could also be done by one entire company but with many departments in charge of operations, maintenance, quality assurance, safety, among others. Each company or department is tasked with ensuring the efficient operation of their assets. However, energy infrastructures are diverse issues, such as:

- Aging and deteriorating infrastructures requiring maintenance and replacement

[13] East, A. (2023). *Oil Gas Electric Comparison.* Mittens Heat Pumps. https://www.mittensheatpumps.co.uk/heat-pumps/oil-gas-electric-comparison/

- Increasing frequency and severity of extreme weather events causing disruptions
- Cybersecurity threats targeting vulnerable systems
- Workforce shortages and skill gaps
- Integrating variable renewable energy sources into the grid contributing to the energy transition

Aging energy infrastructures can lead to failures that pose serious safety risks, such as power outages or environmental hazards. By making sure that the infrastructure is well-maintained, societies and the environment are protected. Another aspect to consider is the fact that old installations can increase inefficiencies, and therefore, operational costs, it is for this reason that investments must be made to reduce operational costs in the long term. Lastly, through this upgrade the energy infrastructures can be adapted to incorporate renewable energy sources, contributing to the energy transition and the sustainability objectives established by the European Union, as well as national governments.

In recent years the effects of climate change, among other factors, have exacerbated natural disasters and have intensified the frequency of extreme temperatures, winters are colder, and summers are hotter. This takes a toll on the existing infrastructures because they were designed for a different time and climate conditions. Consider the example of a hurricane, it is one of the most devastating national disasters since it brings with it a lot of rain and strong winds. Once it touches land it has enough power to wreak everything in its path, communities are decimated, power lines are knocked down because of collapsed tress and heavy winds, many times a hurricane is followed by heavy floods, making it difficult for residents to evacuate, rescue teams to aid the population, and engineers and technicians to tend to the disabled infrastructures. Companies are investing in hardening existing infrastructure to withstand extreme weather conditions, replacing wooden utility poles with more durable materials like steel, burying power lines underground, and reinforcing substations to protect against flooding and high winds; another thing being done is the implementation of smart grid technology which allows for real-time monitoring of energy systems. Lastly, energy companies are adopting frameworks that focus on understanding and mitigating risks associated with extreme weather. These frameworks help identify vulnerabilities in the system and develop strategies to improve resilience. The improvement of the resistance of energy infrastructures against extreme weather is a challenge that requires coordinated efforts in infrastructure investment, technology adoption, regulatory support, and community engagement. Addressing this issue is vital for economic stability, public safety, energy security, and effective climate adaptation.

Figure 2.5: Downed power lines following Hurricane Irma[14]

As technology has advanced so have the threats. Cyberattacks are a risk that 50 years ago were unimaginable, but vulnerable energy infrastructures are now being targeted and various strategies and initiatives are being implemented across the sector to mitigate these risks. These efforts are crucial for protecting energy infrastructures from increasing cyberattacks. Organizations are adopting comprehensive cybersecurity frameworks that include risk assessments, incident response plans, and ongoing monitoring, the frameworks identify vulnerabilities and establish protocols to effectively respond to cyberattacks; as an example, the U.S. Department of Energy recommends keeping in mind cybersecurity into everyday operations and decision-making processes. Energy companies are constantly working with government agencies, cybersecurity experts, and industry partners to share information about threats and best practices; governments are establishing regulatory frameworks to enforce cybersecurity standards in the energy sector, like the NIS Directive in the EU. Cyberattacks can disrupt power generation and distribution, can result in significant financial losses for energy companies and the broader economy, and can be used as tools for geopolitical leverage or terrorism, rendering the cyber protection of energy infrastructures as a crucial matter.

Many energy companies are investing in training programs to teach their workers new required skills. This includes providing opportunities for employees to learn new technologies and processes to adapt renewable energies to the current grids, as well as the installation of renewable energy sources, maintenance of this same equipment, and how to work with battery storage systems. At the same time, partnerships between energy companies and educational institutions are being made to match the study programs with industry needs, ensuring that graduates possess the skills actually required for the transitioning energy industry; this is done through internships and apprenticeships that provide students with practical experience. By ensuring a skilled workforce, companies can improve productivity, foster innovation, and maintain competitiveness in the market. It is important to remember the fact that a well-trained workforce is vital for maintaining the safety and reliability of

[14] M. Comas. (2017, September, 19) *Hurricane Irma: State legislators grill Duke Energy about power outages*. Orlando Sentinel. https://www.orlandosentinel.com

energy systems, since skilled workers are better equipped to handle complex systems and respond to emergencies, reducing the risk of outages and accidents.

Integrating renewable energy sources into the power grid has several issues which can hinder the effective deployment and utilization of renewable energy, impacting grid stability and reliability. One of these issues has to do with how renewable energy sources are intermittent and variable, which can lead to an imbalance in the supply and demand. Solar panels cannot generate any energy on a cloudy day, just as wind turbines cannot generate any energy if there is no wind or winds are not fast enough. The unpredictability of solar and wind resources complicates grid management, requiring additional measures to ensure a stable supply of electricity, because existing power grids were not designed to accommodate variable renewable energy, insufficient transmission capacity and outdated infrastructure can limit the ability to transport renewable energy from generation sites to consumers, especially when these sites are located far from grids. To effectively generate energy from wind and solar, a large amount of wind turbines and solar panels must be deployed to compensate for the variability of these renewable energy sources.

These are some of the detailed issues that are being faced by energy infrastructures, they have to be solved using an innovative approach to promote energy system integration, with coordinated planning and operation of all energy infrastructures. Innovative technologies, policies, and market designs can help modernize and strengthen energy infrastructures for a sustainable future. For simple energy systems an algorithm can be developed to identify the patterns that lead to an energy disruption. However, when it comes to complex energy systems, such as the integration of renewable energies into the power grids, an algorithm might not be the best option to discover the patterns.

Chapter III: Gas Supply Security

In the first chapter the current position of Italy and the European Union on the gas world stage was described, from their gas reservoirs, the domestic production, the pipelines, the policies that regulate the production of natural gas, their shortcomings, the countries they rely on to be able to meet the energy needs of their population, to the potential areas of risk.

The second chapter highlighted what is considered as part of the energy infrastructure related to this hydrocarbon and the entire process and facilities that it goes through for it to become useful for society by being used to generate electricity, its use in the petrochemical industry, heat generation and even for residential use. Lastly, the different challenges being faced by the infrastructures were highlighted as well as its importance and what is being done to mitigate the collapse of these installations.

In this chapter, these previous ideas will be combined and will be put under the scope of the importance of the security of the gas supply of a nation. The gas supply security of a nation, in short terms, is crucial for maintaining economic stability, ensuring social welfare of the respective population, and it helps navigate geopolitical complexities. As global energy dynamics evolve, countries must prioritize the diversification of energy sources, infrastructure investment, and regulatory cooperation to safeguard their gas supplies against future disruptions.

The European Environment Agency (EEA) (2004) defines security of supply in the following way:

> "*… the availability of energy at all times in various forms, in sufficient quantities, and at reasonable and/or affordable prices*."[15]

In the context of this research, energy is substituted for the term of natural gas. Knowing this, and what was discussed in previous chapters, if Italy and the European Union depended entirely on their own domestic production, their security of gas supply would be lacking since the amount of gas extracted domestically is insufficient to meet the demand of its citizens. As a reminder, most of the gas consumed inside these geographical areas is imported from other countries. However, through different agreements made with foreign governments, policies implemented, and the continuous push towards new sources of energy, like renewable energy resources, both parts are able to provide a secure energy supply to their populations.

There have been several notable instances where a lack of security in gas supply, for various reasons, has significantly impacted countries, like Argentina and Chile in 2004; Ukraine in 2006, 2009, and 2014; Japan in

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[15] European Environment Agency (EEA). (2004). *Security of supply*. European Communities. EEA Glossary. https://www.eea.europa.eu/help/glossary/eea-glossary/security-of-supply

2011; Texas in the United States in 2021; and most recently, the entire European Union after the Russian invasion of Ukraine in 2022.

The 2004 Argentine – Chilean Energy Crisis

Argentina and Chile experienced an energy crisis partly due to not investing enough in gas production and infrastructure, Argentina country had to cut gas exports to Chile, impacting Chilean industries and households; Voz de América (2004) reported the following from the, at the time, Chief of Staff of Argentina, Alberto Fernández:

> *"Argentina's Chief of Staff, Alberto Fernández, explained that the problem is the lack of investment by gas producing companies, because for a long time, due to the recession, they stopped investing, but then when things went better for them, they didn't invest either, he said."*[16]

In the early 1990s, Chile and Argentina came to an agreement to build a pipeline that would transport natural gas from Argentina to Chile. However, because of an economic crisis that Argentina was experiencing back then, the Argentine government began imposing price ceilings on natural gas in 2004, which meant that there was less of an incentive for private gas exploration companies to survey the land for more gas reservoirs in the country, since the amount of gas could not be sold above the set limit, this lowered the amount of gas being extracted, as well as the amount of gas being sent to Chile. The price ceiling ended up destroying the domestic natural gas industry in Argentina. Eventually, the entire supply to Chile was cut off, despite protests from the Chileans and attempts at a diplomatic solution. Because of this, Chile began searching for supply alternatives which lead to the construction of liquified natural gas (LNG) terminals inside its territory, making the Argentinian pipeline obsolete. Chile had found a solution to its energy needs, through the facilities it had built, and agreements made with different suppliers, mainly Trinidad and Tobago, it managed to secure a constant delivery of LNG through ships docking at its ports, this LNG would be then regasified and consequently distributed to its final consumers.

The Ukrainian – Russian Gas Dispute of 2006

In 2005 – 2006 Russia claimed that Ukraine was not paying its gas quotas and that it was stealing gas from the EU by diverting itself through pipelines that crossed the Ukrainian territory. Ukrainian officials at first denied the last accusation, but Naftogaz, the national oil and gas company of Ukraine, later admitted that it did use some of the gas intended for other European countries for domestic needs. On January 1, 2006, Russia cut off all gas supply to Ukraine. However, this cutoff also affected gas supplies to Austria, France, Germany, Hungary, Italy, Macedonia, Poland, Romania, Slovakia, Slovenia, which saw a drop of approximately 30% in their supply;

[16] Voz de América. (2009, March, 29). *Chile Reclama a Argentina Cumplir Contratos de Gas - 2004-03-30.* Voz de América. https://www.vozdeamerica.com/a/a-2004-03-30-32-1/77834.html

however, Bosnia Herzegovina, Croatia, and Serbia experienced a drop of 100% to their respective natural gas supplies. On January 4, 2006, a preliminary agreement between Ukraine and Russia was made, where a contract for 5 years was signed the supply was restored and the situation settled down.

Figure 3.1: Vladimir Putin and the then President of Ukraine Viktor Yushchenko hold a joint press conference in Astana on 11 January 2006[17]

The Ukrainian – Russian Gas Dispute of 2009

In 2009, Russia and Ukraine once again had gas disputes. Gazprom, the national oil and gas company of Russia, refused to conclude a gas supply contract it had with Naftogaz unless the latter paid its accumulating debts for previous gas supplies. The dispute began in the final weeks of 2008 with a series of failed negotiations

On January 1, 2009, Russia cut off gas supplies to Ukraine, then on January 7 the dispute turned into a crisis when all Russian gas flows through Ukraine were halted for 13 days, completely shutting off Southeastern Europe from Russian gas. Gazprom and Naftogaz both blamed each other for the problem and on January 11, the EU sent a mission to try and solve the issue, but it had no success. On January 12, Gazprom announced that it was willing to start delivering gas through the Sudzha metering station, highlighted in Figure 2, directly into the pipeline that traverses Ukraine towards Southeastern Europe, but Ukraine refused the offer for technical reasons and instead suggested an alternative route through the Valuyki and Pisarevka metering stations, also highlighted on the map, additionally insisting that supplies be fully restored, which was refused by Gazprom. On January 18, the dispute was resolved when Vladimir Putin and the then Ukrainian Prime Minister, Yulia Tymoshenko, negotiated a new contract that covered the next ten years, two days later, during the morning of January 20, the flow of gas to Europe restarted, and by the 22nd of January the flow of gas had been reestablished to the levels before the crisis started.

[17] Image obtained from Presidential Press and Information Office. (2006, January, 11). *ASTANA. Joint press conference with the President of Ukraine Viktor Yushchenko.* CC BY 4.0, https://commons.wikimedia.org/w/index.php?curid=5507668

Figure 3.2: Major Russian Gas Pipelines to Europe in 2009[18]

The Fukushima Nuclear Disaster of 2011

On March 11, 2011, Japan was hit with a 9.0 Richter-scale earthquake, and a subsequent tsunami, that had its epicenter off the east coast of the region of Tohoku, northeastern Japan. The earthquake resulted in an electrical grid failure of the Fukushima Daiichi nuclear power plant, which started a domino effect, starting with the damage made to almost all of the backup energy sources of the power plant, followed by a failure to cool the reactors efficiently after they shut down because of the detection of the earthquake, however since the switch station had sustained significant damage the power station automatically started up the emergency diesel generators. The inability to properly cool down the reactors after shutdown compromised containment and resulted in the release of radioactive contaminants into the surrounding environment. The following image shows the prefectures of Tohoku, including the Fukushima prefecture:

[18] Image obtained from Samuel Bailey (sam.bailus@gmail.com) - Own work, CC BY 3.0 nz, https://commons.wikimedia.org/w/index.php?curid=8642475

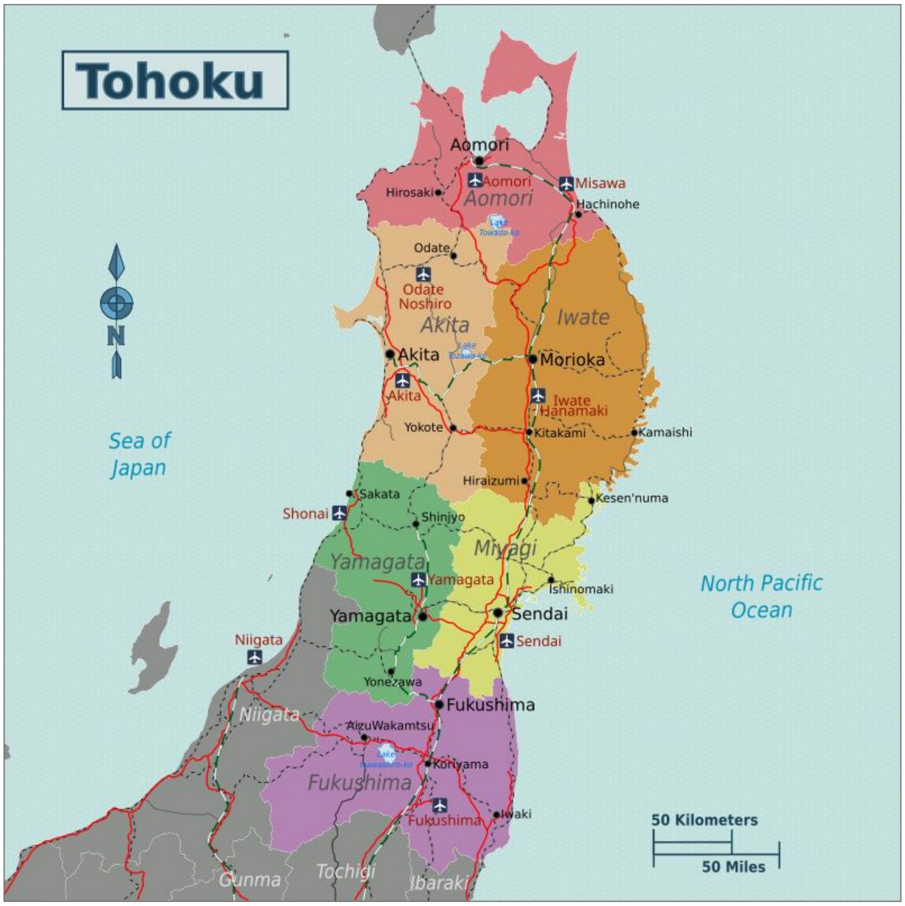

Figure 3.3: Prefectures and major cities in Tohoku[19]

In the days after the disaster, the Japanese government shut down many nuclear power plants across the country and increased its reliance on imported LNG, as it was highlighted by Jane Nakano in 2011:

> *"Japan has over 40 operating terminals to import liquefied natural gas (LNG). Only one small re-gasification terminal in Miyagi prefecture shut down as a result of the earthquake. The general health of LNG importing facilities would allow Japan to continue importing LNG and potentially compensate for some of the loss in nuclear power capacity."*[20]

The Ukrainian – Russian Gas Dispute of 2014

On the 1st of April 2014, Gazprom cancelled a discount Ukraine had on its supply of Russian natural gas as it had been agreed in the Ukrainian–Russian action plan of December 17, 2013. The cancellation of the discount was because the debt Ukraine had with Gazprom had risen to $1.7 billion since 2013. At the same time, Russia raised the price of gas to $485 per 1000 m^3. During the first days of May of 2014, trilateral talks began between Russia,

[19] Image made by T.Kambayashi - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=22745809

[20] Nakano, J. (2011, March, 23). *Japan's Energy Supply and Security since the March 11 Earthquake*. Center for Strategic and International Studies (CSIS). https://www.csis.org/analysis/japans-energy-supply-and-security-march-11-earthquake

Ukraine and the, at the time, Energy Commissioner of the European Union, Günther Oettinger. These negotiations had some success when on May 30, 2014, Ukraine paid $786 million to Gazprom; however, further negotiations failed on June 15, 2014. In the morning of June 16, 2014, Russia stopped all flow of natural gas to Ukraine, and later in the day, Gazprom stated that the debt Ukraine had towards the company was $4.5 billion, it also assured the EU that its supply of gas would not be affected, and that future payments for this hydrocarbon made from Ukraine to Gazprom had to be upfront. After months of negotiations between the European Union, Ukraine and Russia, an agreement was made on October 30, 2014, where Ukraine agreed to pay, upfront, $378 per 1000 m^3 until the end of 2014, and $365 per 1000 m^3 during the first quarter of 2015. Simultaneously, Ukraine agreed to pay off part of its debt by agreeing to pay $1.45 billion immediately, and $1.65 billion by the end of 2014. It was agreed that the European Union would be acting as a guarantor for future Ukrainian gas purchases from Russia, as well ensuring that Ukraine paid off all remaining debts. The total economic package was worth $4.6 billion, completely wiping out the debt Ukraine had with Gazprom of $4.5 billion, this deal made European Union officials feel secure since there would be no disruptions of natural gas supply to other European nations.

The Great Texas Freeze of 2021

Starting on February 11 and ending on February 20, 2021, the state of Texas in the United States of America was hit by a series of winter storms that engulfed the entire state under a record number of snow and cold temperatures, this event came to be known as The Great Texas Freeze of 2021. The Freeze was caused by multiple factors, but there were two of them that stood out, the strongly negative Arctic Oscillation and the disrupted polar vortex.

The Arctic Oscillation refers to the fluctuation of atmospheric pressure between the Arctic and the mid-latitudes of the North Pacific and North Atlantic. This oscillation affects weather and climate patterns across North America, Europe, and Asia, particularly during the winter months. When the Arctic Oscillation is negative, the weakened jet stream shifts further south, allowing cold Arctic air to penetrate deeper into southern regions.

The polar vortex is a large area of low pressure and cold air that encircles the poles of the Earth, like a loop. When this vortex weakens or is disturbed, the jet stream can become highly wavy, allowing warm air to flow into the Arctic while cold polar air moves down into the mid-latitudes.

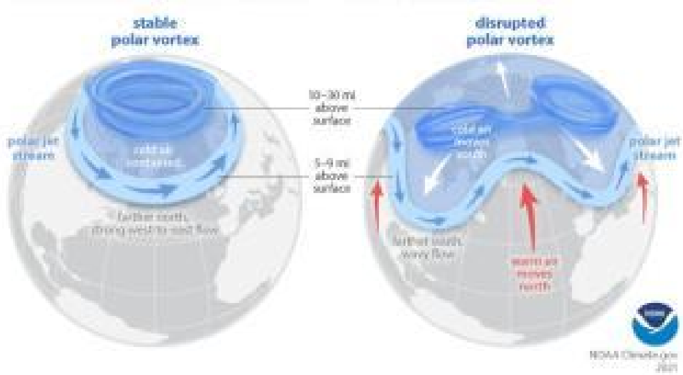

Figure 3.4: Comparison between a stable and disrupted polar vortex[21]

The storms triggered the worst energy infrastructure failure in the history of the Lone Star State, leading to shortages of water, food, and heat. Data showed that the failure to prepare power sources for the winter and cold temperatures, mainly natural gas infrastructures, had caused the failure of the power grid, with a drop in power production from natural gas. Approximately 4.5 million homes and businesses were left without power. The full impact of the natural disaster, from an energy point of view, is best described by the National Centers for Environmental Information, NCEI (2023):

> *"Though power outages occurred throughout the South, they were mostly concentrated in Texas. At the peak of the outage, nearly 10 million people were in the dark, lacking warmth and the ability to cook food. The freeze also caused water pipes to burst and boil water advisories were issued in many counties."*[22]

The Russian Invasion of Ukraine of 2022

As it has been discussed in previous chapters, and as the current example of gas supply security, the invasion of Ukraine by the armed forces of the Russian Federation has made the entire EU rethink its strategies regarding the security of its gas supply. The EU has imposed sanctions on Russia and has changed it suppliers – as a reminder, Algeria, the United States, Norway, and Qatar are now the main suppliers of natural gas to the EU.

The European Commission (2004) summarized the situation of the EU with its supply of natural gas and the actions taken against Russia in the following way:

> *"About one-quarter of all energy used in the EU comes from natural gas. Maintaining a secure supply is therefore essential to ensuring energy security for EU citizens and businesses.*

[21] Image obtained from the National Oceanic and Atmospheric Administration, NOAA. (2021). https://www.ncei.noaa.gov/sites/g/files/anmtlf171/files/PolarVortex_Feb2021_620-Edited.jpg

[22] National Centers for Environmental Information, NCEI. (2023, February, 24). *The Great Texas Freeze: February 11-20, 2021*. National Oceanic and Atmospheric Administration, NOAA. News. https://www.ncei.noaa.gov/news/great-texas-freeze-february-2021

Gas supply disruptions may result from technical or human failures, natural disasters, cyber-attacks and other emerging risks or geopolitical disputes.

Many EU countries import nearly all their supplies and some are, or have been, also heavily reliant on a single source, meaning that disruptions along a single transport route can threaten the certainty of their gas supply.

Russia's unprovoked and unjustified full-scale military invasion of Ukraine in February 2022 and its attempted weaponization of Europe's security of energy supply is a key example. It highlighted the EU's over-dependence on a single, unreliable supplier for almost half of its gas imports.

Since May 2022, the EU has taken a range of actions to eliminate its reliance on Russian fossil fuel imports by saving energy, diversifying supplies and accelerating the roll-out of renewable energy production in Europe."[23]

The strategies take by the EU against Russia have made the fossil fuel imports coming from the Russian Federation drop from 90 billion euros in 2019, to 7 billion euros in 2023, a 92% decrease in these hydrocarbons.

From the previous examples, it can be concluded that gas supply disruptions can happen for many reasons, such as technical failures, natural disasters, geopolitical issues, and other situations. Ensuring the security of the gas supply of a nation is crucial for several reasons, particularly in the context of energy independence, national security, economic stability, social welfare, and geopolitical considerations.

A nation that achieves energy independence is less susceptible to political or economic pressure from other countries, allowing them to make decisions in domestic and foreign matters that do not have the added pressure of considering what the country from which they are importing an amount of gas thinks. As it was detailed in the previous examples, particularly the ones related to Russia and Ukraine, energy independence gives countries greater leverage in international negotiations, granting them the freedom to pursue their interests more assertively during negotiations. By reducing reliance on energy imports, a nation strengthens its security and its economy, becoming less vulnerable to supply disruptions during conflicts or geopolitical tensions as it happened on several occasions to Ukraine. Domestic energy production also shields the economy from global market volatility, mitigating the effects of sudden price spikes or supply shortages, as was the case for Chile because of the economic crisis that Argentina was going through.

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[23] European Commission. (2004). *Security of Gas Supply.* European Commission. Energy. https://energy.ec.europa.eu/topics/energy-security/security-gas-supply_en

Furthermore, the development of domestic gas reservoirs and the investment in renewable energies creates more jobs and stimulates economic growth contributing to the strengthening of the economy of a country. Additionally, it grants a nation greater control over its energy policies, enabling more effective management of environmental regulations and facilitating the transition to renewable energy sources. In times of natural disasters that may disrupt supply chains, nations that are more independent are better equipped to maintain a stable energy supply. Good lessons can be taken from the cases of Texas (with an electricity system that was poorly connected to the rest of the grid of the United States, showing that interconnections are valuable) and Japan (with an increasing dependency on external energy sources whilst diminishing the use of nuclear power).

Gas is a vital energy source for many countries, especially in Europe, where it makes up a large part of electricity generation and is essential for heating and industrial processes. Disruptions in gas supply can lead to increased energy prices, affecting everything from manufacturing costs to consumer prices. As was mentioned previously during the strategies implemented by the EU after the beginning of the Russian-Ukrainian conflict, gas is the marginal supplier in the electricity mix, meaning that fluctuations in gas availability can directly impact electricity prices.

Touching on the topic of national security, armed forces rely heavily on energy for operations, training, and logistics. A stable gas supply contributes to military readiness and the ability to respond to threats or emergencies. At the same time, modern gas infrastructures are becoming increasingly more digitized. Ensuring supply security also involves protecting these systems from cyber-attacks that could disrupt energy distribution in case of a national emergency.

Gas supply security is also integral to social services. Many households depend on gas for heating, cooking, and other essential needs. A reliable gas supply ensures that these basic services are covered, particularly during peak demand periods, such as winter and summer months. Disruptions can threaten public health and safety, making it crucial for nations to have measures established to protect vulnerable populations.

As a concluding remark, securing the gas supply of nation in the face of geopolitical, technical, and economic challenges is of the outmost importance. Gas supply disruptions can arise from various sources, as was seen in the many examples presented, making energy independence vital for ensuring national security, economic stability, and social welfare. By decreasing the dependence of a nation on external energy sources, countries not only enhance their geopolitical leverage but also protect their economies from market volatility and supply shortages. Moreover, the development of domestic reservoirs, along with investments in renewable energy, creates jobs, fosters economic growth, and provides more control over energy policies, including environmental regulations. Secure gas supply is essential for critical sectors such as military readiness, industrial processes, and social services. Ultimately, a nation that achieves energy independence is better equipped to maintain stability in the face of crises, securing the well-being of its citizens and the resilience of its infrastructure.

Chapter IV: Early Warning Systems

As it has been thoroughly discussed previously, gas supply security is crucial for the economic and social development of countries, and there are many factors at play, from natural disasters to geopolitical conflicts. Although it is impossible to predict when will the next hurricane, earthquake, or even war might occur, it is possible to analyze data received from different sources, to evaluate and assess a situation, in order to better support the decision making regarding the best course of action. In this chapter, the methodology of how information is collected, analyzed, and processed to aid in decision-making situations is described. The approach to be presented is based in the widely employed concept of early warning systems.

An early warning system (EWS) is a system that, after gathering and analyzing relevant data, produces alerts informing that there are some indications that a negative situation, for whatever case, might unfold. Given this alert, the analysts should first search for further information in order to confirm the negative situation, and then - if so – deploy countermeasures to mitigate the impact or completely avoid the contingency . For example, think of a traffic light, while the light is green cars are allowed to proceed across the intersection and continue their journey. Once the light turns yellow, it is notifying the driver that the flow of traffic will soon be halted, once the light turns red. Once the light is red, the driver must stop in order to avoid an accident while crossing the intersection. This yellow light is the equivalent of an early warning.

Figure 4.1: Simplification of an early warning system

Scaling up this example, and taking it into another context, think of the war between Ukraine and Russia. A couple of days before the Russian invasion, the United States issued a warning to all its citizens living in Ukraine, and especially those living in the regions nearest to the Russian border, telling them to evacuate the country because the Early Warning Systems of the United States, using the information they collected, indicated that an invasion was imminent. This alert signal was given because their systems received data that pointed towards a probable attack. One can only speculate as to what kind of information did the systems receive, it could have been the fact that days before the invasion president Putin started mobilizing his troops towards the Ukrainian border under the excuse of it being a training exercise, or the posts on social media by Russian soldiers, or young men who had been called to enlist in the Russian army. These elements are examples of the information that was gathered by the Early Warning System of the Department of Defense of the United States.

An informal example of what an Early Warning System can be is provided by strip clubs. These establishments handle a lot of cash on site, it is where businessmen take potential clients to negotiate and have a good time. In New York City, when the market is good and they have extra cash to spare, men like to go and spend their money in these places, they have money to spend so they can make frivolous expenses. However, if the economy is not doing too well, clients do not go out spending their money on these businesses. The strip clubs notice this, and the workers can tell when the economy is doing well or not. If the economy is doing well, they will have more clients, if it is not doing well the establishment has less people and therefore the strip club workers have less of a reason to go to work. This is an informal indicator of the economic cycle.

Another example of an Early Warning System under the scope of natural disasters can be given by Mexico and its seismic alarm system. Mexico is a country that is prone to earthquakes, especially Mexico City, the capital of the nation. Mexico City was founded on top of the basin of a drained lake, the city is constantly sinking, and it is unstable, whenever an earthquakes hits, the seismicity is amplified because of this. In 1985, Mexico suffered one of its biggest earthquakes in the XX century, on September 17, at seven in the morning, an earthquake of 8.0 magnitude on the Richter scale hit the capital, destroying many buildings and leaving a significant death toll. After the reconstruction of the city, in 1989 the Mexican Government decided to install seismometers along the Mexican Southwestern coast, since this is the part of the country that lies on top of the North American Plate, bordering the Cocos Tectonic Plate. Every vibration is registered, however there are threshold values which must be surpassed for the alarm to go off. The alarm will set off if:

- The earthquake occurs less than 170 kms from Mexico City, and is over 5.0 on the Richter scale;
- The earthquake occurs between 350 and 170 kms from Mexico City, and is over 5.5 on the Richter scale;
- The earthquake occurs more than 350 kms from Mexico City, and is over 6.0 on the Richter scale.

Once the geophones register a strong enough vibration, the signal is sent to Mexico City where the alarm goes off, alerting the citizens that they have approximately one minute to get to safety before the earthquake hits.

In these examples, it is evident that an Early Warning System learns from previous events and discovers patterns that may, or not, be structured. Based on these structured patterns, the system can monitor what happens in real time and it can identify said patterns to find a match, as was the case with the Mexican Earthquake Alert System with its threshold values. History matching is not always direct, and with real industrial systems being complex (as is the case with energy systems), the available or accessible current information could be incomplete and have different levels of uncertainty.

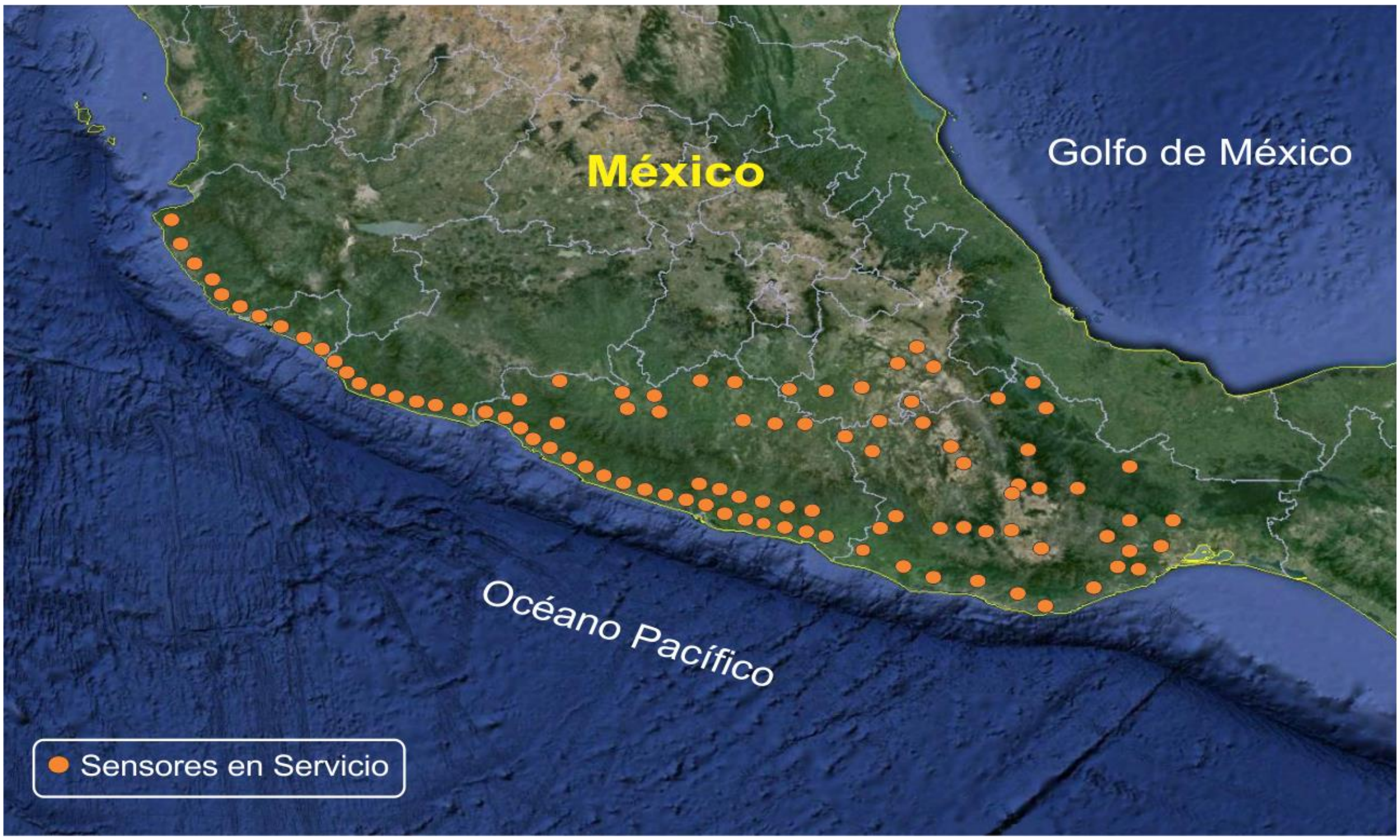

Figure 4.2: Location of the earthquake sensors along the Mexican seismic propensity zone[24]

Now that the concept of what an early warning system is, as well as examples of it in different contexts, we can take switch to see how early warning systems might work under the light of energy supply security.

Amongst different ongoing conflicts around the world, nations must assure a constant supply of energy to satisfy their national demand. However, it is impossible to predict when and where the next issue in this long supply

[24] Centro de Instrumentación y Registro Sísmico, A.C. (2024). *Sistema de Alerta Sísmica Mexicano.* Gobierno de la Ciudad de México. SASMEX. http://www.cires.org.mx/sasmex_n.php

chain will occur, but it is possible, by looking at their geopolitical relations, at information of different hazards (such as natural ones), and threats (such as cybersecurity), to take precautions and try to guarantee a continuous influx of energy.

The objective of an early warning is to alert a government and/or an energy company about a potential energy crisis due to geopolitical, economical or a social situation, giving time for the leaders of a country and/or of the company to take the appropriate countermeasures to mitigate the risk.

Early Warning Systems around the world

Based on the available information, it is clear that a majority of countries have established their own alarm systems that advise them to take adequate countermeasures and mitigate the risk of loss of energy supply. The following list is made up of some countries who are members of the G7, as well as Russia and China.

The events that could set off the early warnings are similar in between all the countries considered in this research. However, they all have different policies to assess the cause for alarm and start looking for solutions to not disrupt their energy supply. Even though some nations might have different political viewpoints, in the end they still depend on each other on some level. The Russian – Ukrainian conflict was an early warning for many countries that are aligned with the West but rely on the supply of Russian gas, as was the case for Germany.

In other cases, a country might adapt another the energy security system of another country to its own needs, as is the case for the United Kingdom that uses the Energy Security Risk Index made by the Chamber of Commerce of the United States to be ready for any potential energy crises.

When it comes to energy security, an early warning system gives a government time to think about what it needs to do to mitigate an energy risk, if said issue escalates. It also allows a nation to rethink their energy strategies and continue working towards self-sufficiency.

Italy

The Italian natural gas early warning system is governed by the Italian natural gas system's Emergency Plan which is an annex to the Ministerial Decree of October 18th of 2017.

The early warning level is established to correspond to whenever there is concrete, serious, and reliable information that an event may occur which is likely to result in significant deterioration of the supply situation and is likely to lead to the alert or the emergency level being triggered.

The activation mechanism consists in the occurrence of one of the following conditions:

- the occurrence of events leading to a significant reduction of imports, absent a concrete, serious, and reliable information on the short-term return to normality.
- the forecasting of an exceptionally high total daily gas demand observed statistically once every twenty years, or of unfavorable climatic events of exceptional geographical extent capable of significantly deteriorating the non-domestic supply situation.
- the attainment even for just one day of a daily volume withdrawn from storage system larger than 100% of the daily withdrawal capacity available, net of withdrawal capacities allocated on monthly, weekly, daily bases from the Main Storage operator.

The declaration of the early warning level is made by the Competent Authority, having received feedback from the Technical Gas – System and Monitoring Committee, which was established according to article 8 of the Italian Ministerial Decree of September 26th 2001upon warning of the main transmission system operator, which:

- shall communicate that the early warning level has been declared, also by means of a specific publication on its website.
- shall regularly communicate the update of the situation to the Competent Authority and to the Committee, for the monitoring and for the possible assessments regarding transition to the alert level or the termination of the early warning level.

The lifting of the early warning status is declared by the Competent Authority, as a rule not before 48 hours after the fading of the activation conditions, based on favorable medium-term forecasts about the evolution of the gas system carried out by the main operator. The main operator shall communicate the early warning status end, also by a specific publication on its website.

France

French policies to enhance natural gas security of supply are based on two pillars:

- Risk mitigation: planning of gas supply to meet expected demand and market regulation in the form of public services obligations on all gas sector players.
- Emergency response policies: an emergency action plan divided into three levels: early warning, alert level, and emergency level.

In case of an emergency and when preventive actions (increase of supply, by-passing of certain infrastructure, etc.), are not sufficient to satisfy French customers' demand, specific measures are foreseen in the emergency plan. The main mechanism to manage a gas crisis is targeted gas curtailment – a new framework for gas curtailment has been introduced and was completed in 2021.

The emergency plan foresees three crisis levels:

- Early warning level: when there is concrete, serious, and reliable information that an event may occur which is likely to result in significant deterioration of the supply situation and is likely to lead to the alert or the emergency level being triggered.
- Alert level: when a supply disruption or exceptionally high gas demand occurs which results in significant deterioration of the supply situation, but the market is still able to manage that disruption or increased demand without the need to resort to non-market measures.
- Emergency level: in the event of exceptionally high gas demand, a significant supply disruption or other significant deterioration of the supply situation, and if all relevant market measures have been implemented but the supply of gas is still insufficient to meet the remaining gas demand, so that non-market measures must be additionally introduced.

Germany

Early warning indicators regarding energy security in Germany are implemented through a structured system outlined in the Emergency Plan for Gas for the Federal Republic of Germany. This plan defines three crisis levels which are used to monitor and respond to potential risks to gas supply security:

- Early warning level
- Alert level
- Emergency level

The early warning level is declared by the Federal Ministry for Economic Affairs and Climate Action based on concrete and reliable information indicating a significant deterioration in the gas supply situation. The full procedure of the early warning procedure is detailed in the table below.

Early Warning Level	
Competent authority responsible for declaration	Federal Ministry for Economic Affairs and Climate Action (BMWK)
Description in line with Regulation (EU) 2017/1938	There is concrete, serious, and reliable information that an event may occur which is likely to result in significant deterioration of the gas supply situation and is likely to lead to the alert or the emergency level being triggered.
Declaration procedure	In the case of the early warning level, this is primarily a political decision taking the form of a declaratory measure. It is declared by a press release.

Indicators for the declaration of the early warning level	Taking place separately or together: - absence, lack or reduction of gas flow at key physical entry points, - long-lasting low gas reservoir storage levels, - shutdown of important sources of supply, - technical failure of major infrastructure, e.g. pipelines and/or compressor station failure, - extreme weather conditions coupled with high demand, - risk of long-term shortage, - declaration of a crisis level in a neighboring country.
Termination procedure	When the indicators no longer apply, the BMWK ends the early warning level via a statement published on its website and informs the European Commission about this. The lifting of the early warning level signifies a return to normal operations.
Reporting obligations	- At national level • Participation of the players in the meetings of the federal crisis team. • Information in line with section 15 (2) Energy Industry Act o Necessary information to ensure that the transport and storage of gas can take place in a manner which can be aligned with the secure and efficient operation of the interconnected system provided by operators of transmission systems, storage, or LNG installations to every other operator of a gas supply system with which their own transmission systems or installations are technically connected. o Information on the secure and reliable operation of transmission systems by electricity transmission system operators to gas transmission system operators. • Information in line with section 10 (1) Energy Security of Supply Act on the enactment and preparation of the statutory instruments in line with section 3 Energy Security of Supply Act. • Information in line with section 2b (2) Energy Security of Supply Act and in line with section 1a Ordinance to Ensure the Supply of Gas in a Supply Crisis on the operation of the Gas Security Platform (SiPla). - At the European level

	• Information especially about planned measures in accordance with Article 11 (2) and (4) and Article 14 Regulation (EU) 2017/1938 to
	  ○ the European Commission (possibly via a data platform set up by the Commission),
	  ○ the competent authorities of the risk groups,
	  ○ the EU Member States with which Germany is connected by infrastructure,
	  ○ Switzerland.

Table 4.1: Stipulation and procedures for the declaration and termination of the early warning level[25]

On March 30th, 2022, Germany declared its first early warning level in the Emergency Plan for Gas after Russia threatened to cut the supply of gas after the German Republic and G7 countries rejected the Russian demands for gas payments to be made in Rubles, as reported by S&P Global:

> *"Germany has declared a first early warning level in its national gas emergency plan, energy ministry Robert Habeck said March 30.*
>
> *The plan was put in place amid a threat of Russian cuts to gas supplies after Germany and G7 countries rejected Russian demands for gas payments in Rubles, it said.*
>
> *Security of supply continued to be guaranteed with no supply shortages, the ministry said.*
>
> *"Nevertheless, we must step up precautionary measures in order to be prepared in the event of an escalation from Russia," the energy minister said.*
>
> *The first of three warning levels is triggered when there is a serious risk of disruption.*
>
> *It requires a crisis team to evaluate the supply situation so that, if necessary, further measures can be taken to increase security of supply, the ministry said.*
>
> *The second alert level is activated when there is a disruption to gas supply or exceptionally high demand for gas, leading to a significant deterioration in supply.*
>
> *The final state of emergency is declared when there is exceptionally high demand for gas or significant disruption to gas supply, with all market-based measures implemented and supply still insufficient.*

[25] Ministero delle Imprese e del Made in Italy. (2017, October 17). Italian natural gas system's Emergency Plan. Annex 2 to the Ministerial Decree of 18th October 2017.

In this case non-market-based measures can be taken."[26]

United States

The U.S. Chamber of Commerce has developed an "Energy Security Risk Index" that serves as an early warning system for potential energy crises. This index incorporates a diverse set of quantitative indicators spanning physical, economic, environmental, and geopolitical dimensions of energy security. The goal of the Global Energy Institute in developing the Index of U.S. Energy Security Risk was to use available data and forecasts to develop the metrics that collectively describe the geopolitical, economic, reliability, and environmental risks that measure the risk to overall U.S. energy security in a single Index.

The various metrics that support it are designed to convey the notion of risk, in which a lower index number equates to a lower risk to energy security and a higher Index number relates to a higher risk. This notion of risk is conceptually different from the notion of outcome. Periods of high risk do not necessarily lead to bad outcomes just as periods of low risk do not necessarily lead to good outcomes.

The following image shows how the Index of U.S. Energy Security Risk is built.

[26] Franke, A. (2022 March 30). Germany declares first early warning level in national gas emergency plan. S&P Global https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/natural-gas/033022-germany-declares-first-early-warning-level-in-national-gas-emergency-plan

Figure 4.3: U.S. Energy Security Risk Index[27]

China

An early warning indicator system of the oil system in China which covers 23 sub-indicators from the aspects of resource security, market security and consumption security, was constructed using a statistical method. This indicator shows that oil system security level of China has been seriously threatened and is declining. However, these threats have been eased due to the strong introduction of energy policies and increasing energy utilization technology in recent years, as well as the increasing proportion of new energy, renewable energy, and oil substitutes.

The construction of the oil system early warning indicator system aims to obtain highly reliable trends of oil security through mathematical analysis and compare them with representative index data. Since there is no widely

[27] Global Energy Institute. (2020). Index of U.S. Energy Security Risk, Assessing America's Vulnerabilities in a Global Energy Market. U.S. Chamber of Commerce.

acknowledged standard system currently, ensure that the calculation results are objective and scientific, the index system was constructed in the following way:

1. The systematic and complete construction of the indicator system was ensured. The indicator system was constructed from the aspects of resource security, market security and consumption security.
2. The indicators are selected according to reliability by means of:
   i. Ensuring that the indicator is easy to quantify and obtain.
   ii. Using quantitative indicators as much as possible to correct for the uncertainty brought by qualitative indicators.
   iii. Applying recognized methods to evaluate the indicator system to avoid the uncertainty of outputs.

A total of 23 indicators were selected to construct the oil early warning system of China from 2001 to 2015.

Element	Indicator	Abbr.	Unit	Meaning
Resource security	Proportion of oil reserves in the world total oil reserves	R_1	%	Domestic oil recoverable reserves/world oil recoverable reserves
	Reserve-production ratio	R_2	%	Domestic oil remaining recoverable reserves/domestic oil production
	China's oil reserves per capita	R_3	t/person	Domestic oil reserves/domestic population
	Oil production growth rate	R_4	%	(Annual oil production − the production of the previous year increments)/the previous year oil production
	Proportion of oil production in the world total oil reserves	R_5	%	Domestic oil production/world oil production
	Reserve replacement rate	R_6	%	Newly verified oil recoverable reserves/current annual consumption of oil reserves
	Efficiency of oil process and conversion	R_7	%	Oil processing conversion output/oil processing conversion input
	Proportion of oil production	R_8	%	Oil production/China's total energy production
Market security	International oil price	M_1	USD/barrel	Current price of oil
	International oil price volatility rate	M_2	%	(Current price of oil − base period oil price)/base period oil price
	Supply and demand balance ratio	M_3	%	China's total oil supply/China's total oil consumption
	Import dependence rate	M_4	%	(Domestic oil imports − domestic oil exports)/domestic oil consumption
	Import source concentration rate	M_5	%	Sum of top 5 countries or regions oil imports/total imports
	Consumption of oil imports to GDP(gross domestic product)	M_6	%	GDP consumed by domestic oil imports/current GDP
	Oil import share	M_7	%	Oil imports/international market oil trade
	Oil industry price index	M_8		Indicators for measuring changes in ex-factory prices and changes in the prices of industrial products
Consumption security	Proportion of consumption	C_1	%	Oil consumption/total energy consumption
	Oil consumption intensity	C_2	t/RMB	Domestic oil consumption/domestic GDP
	Oil consumption elasticity coefficient	C_3	%	Oil consumption growth rate/GDP growth rate
	Oil consumption growth rate	C_4	%	Current year's oil consumption growth/last year's oil consumption × 100% − 1
	Oil saving rate	C_5	%	(1 − current annual oil consumption per unit of GDP/the previous year's oil consumption per unit of GDP) × 100%
	Ratio of oil production growth rate to consumption demand growth rate	C_6	%	Oil production growth rate/consumption demand growth rate
	Oil share of primary energy consumption	C_7	%	Annual oil consumption/total annual primary energy consumption

Figure 4.4: Oil early warning indicator system and the interpretation of each indicator for the system in China[28]

As it has been discussed in previous chapters, energy demand has been rising due to technological advancements, urbanization, population growth, global trade, and climate change. Despite the growth of renewable energy sources, fossil fuels remain dominant, accounting for about 80% of global energy use, as was seen in chapter 2.

[28] Qingsong W. et al. (2018). An Early Warning System for Oil Security in China. Sustainability. MDPI. vol. 10(1). pages 1-17.

Energy crises often result from supply-demand imbalances, geopolitical risks, economic disruptions, and natural disasters. Historical energy crises have led to significant changes in international trade and monetary systems.

In March of 2024, Turgut Yokus published an article titled *Early Warning Systems for Energy Security for World Energy Crises*[29], where he developed an early warning system to predict world energy crises. Energy crises have significant economic, political, and social impacts, including inflation, economic downturns, and geopolitical tensions. The objective of the paper was to identify the determinants of energy crises using a binary logit model, analyzing data from January 1973 to December 2022.

While consulting articles for his research, Yokus categorized studies into three groups:

- those focusing on the causes and economic consequences of energy price shocks,
- those examining energy price volatility,
- those identifying determinants for forecasting energy prices.

In his results he proved how much of an impact does the price of oil have on macroeconomic variables like inflation, interest rates, and employment. The volatility of energy prices is often linked to macroeconomic uncertainty, financial speculation, and geopolitical risks.

Model Development

The EWS model for energy crises of Yokus was developed using logistic regression (LR) analysis. The model includes three main components:

1. The crisis index (which is a dependent variable that is binary, meaning that it can only take on values of either 0 or 1 at each observation) in this case it is the Energy Market Pressure Index (EMPI)
2. Explanatory variables
3. Method of analysis

Logistic Regression

Logistic regression is used to estimate the probability of an energy crisis based on a set of early warning indicators. The model calculates the odds ratio to interpret the likelihood of a crisis. It predicts energy crises by estimating the probability that a crisis will occur based on a set of explanatory variables. The model works in the following way:

1. Dependent Variable (Energy Market Pressure Index - EMPI)

[29] Yokus, T. (2024, March 9). Early Warning Systems for Energy Security for World Energy Crises. Sustainability 2024. MDPI. https://doi.org/10.3390/su16062284

The dependent variable, EMPI, is constructed using the energy price index and US inflation data. The model identifies a crisis when the EMPI exceeds a certain threshold, typically set at 2 standard deviations above the mean.

- If EMPI = 0, no energy crisis
- If EMPI = 1, energy crisis

2. Explanatory Variables

The explanatory variables are selected based on their relevance to energy prices and crises. These include indicators related to energy supply and demand, economic and financial markets, investments, geopolitical risks, and expectations. The final model includes 13 explanatory variables, which were selected based on their relevance to energy prices and crises. These variables cover aspects such as energy supply and demand, economic and financial markets, investments, geopolitical risks, and expectations. The selected variables are:

1. Consumer price indices in G7 countries (CPIG7),
2. Dollar index (DXY),
3. Crude oil, natural gas, and dry wells, total footage drilled (FD),
4. G20 composite leading indicator (G20CLI),
5. Gold on-the-spot price (GOS),
6. Geopolitical risk index (GPRH),
7. Global real economic activity index (GREAICI),
8. Total fossil fuel production/total primary energy production (FP/PEP),
9. US total petroleum stocks (PS),
10. US petroleum imports from total non-OPEC countries (INOPEC),
11. Petroleum imports from total OPEC (thousand barrels per day) (IOPEC),
12. US total primary energy consumption (quadrillion btu) (PEC),
13. Total primary energy production (PEP)

3. Logistic Regression Equation

The logistic regression model estimates the probability of an energy crisis occurring using the following equation (Eq.1):

$$P(Y_t = 1) = \frac{exp(X_t\beta)}{1 + exp(X_t\beta)}$$

Where:

Y_t, is the dependent variable, energy market pressure index (EMPI), with a value of 0 or 1.

X_t, represents the explanatory variables.

β, represents the model parameters and the model uses the maximum likelihood method to estimate the parameters of the logistic regression equation.

The dependent variable is determined using the following equation (Eq. 2):

$$Y_t = \begin{Bmatrix} 1, EMPI_t > \mu_{EMPI} + 2\sigma_{EMPI} \\ 0, EMPI_t \leq \mu_{EMPI} + 2\sigma_{EMPI} \end{Bmatrix}$$

Where:

μ_{EMPI}, is the mean of the energy market price index.

σ_{EMPI}, is the standard deviation of the energy market price index.

Lastly the odds ratio, which is calculated to interpret the likelihood of a crisis and helps understand how changes in the explanatory variables affect the probability of a crisis, is calculated using the following equation (Eq. 3):

$$exp(X_t\beta) = \frac{P(Y_t = 1)}{1 - P(Y_t = 1)}$$

4. Model Estimation

The estimation process involves fitting the model to historical data from January 1973 to December 2022, using monthly observations. However, the model has some limitations, including the availability of data and the exclusion of certain indicators like NYMEX, VIX, and world oil stocks, world energy production and consumption, and world energy import-export data. Therefore, the study assumes that the selected 13-variable model is the most consistent and accurate predictor.

5. Prediction and Thresholds

The model generates a predicted probability for each time period. A threshold value is set to classify whether a crisis is predicted or not. The common threshold values are 0.25 and 0.5. If the predicted probability exceeds the threshold, the model predicts a crisis (1); otherwise, it does not predict one (0). The model reaches an overall prediction accuracy of 99%.

6. Model Performance

The performance of the model was evaluated using statistical tests like the McFadden R-squared, LR statistic, and Hosmer and Lemeshow test. The predictive accuracy of the model was also assessed by comparing the predicted crisis periods with the actual observed crisis periods; the model is quite robust, consistent and is able to provide statistically significant results.

7. Results interpretation

Variables with positive coefficients increase the probability of a crisis when their values rise. For example, an increase in the G7 inflation index (CPIG7) or the geopolitical risk index (GPRH) raises the likelihood of a crisis. On the other hand, variables with negative coefficients decrease the probability of a crisis when their values rise. For instance, an increase in the dollar index (DXY) or oil stocks (PS) reduces the likelihood of a crisis.

The logistic regression model predicts energy crises by estimating the probability of a crisis based on a set of explanatory variables. It uses historical data to fit the model and generate predictions, which are then classified using a threshold value. The performance of the model is evaluated through various statistical tests to ensure its robustness and accuracy.

The EWS model of Yokus successfully identifies the determinants of energy crises, including supply-demand imbalances, economic disruptions, and geopolitical risks. The indicators of the model align with those identified by the US Energy Information Administration (EIA) and other studies. The study suggests that the model can provide early warnings, allowing policymakers to take preventive measures. However, further research must be done by including new explanatory variables, such as energy market financialization factors and private sector investments. Other methods like the signaling approach and machine learning could also be explored to compare the estimation results.

For further details on how the early warning system to determine energy crises developed by Turgut Yokus works, please consult his article *Early Warning Systems for Energy Security for World Energy Crises.*

Chapter V: The Role of Artificial Intelligence in Early Warning Systems

As seen in the previous chapter there are methods used to anticipate energy crises, however they are purely statistical, taking information from the past to make probabilistic estimations into the future.

We are currently living in the era where artificial intelligence is growing at a rapid rate, being used more and more in all kinds of applications, and early warning systems are no exception. Maria Teresa Della Mura in her 2024 article *"Early warning systems: harnessing AI to mitigate risks"* [30] talks about how early warning systems are essential in mitigating the impacts of extreme weather events, particularly floods, like the ones that happened in Italy, Libya, and Asia, at the beginning of 2024. These natural disasters are more and more frequent and severe due to climate change and have more than doubled since 2000. The integration of different artificial intelligence techniques (such as machine learning) can play a key role in enhancing forewarning capacities, especially in under-monitored regions, and supports damage assessment and emergency response after disasters. The use of artificial intelligence can improve the effectiveness of early warning systems, helping reduce fatalities and economic damage. For instance, expanding global flood prediction and early warning systems, especially in vulnerable areas, can save lives and reduce economic losses. Effective land management, improved forecasting, and multi-hazard early warning systems are vital in order to adapt to the growing risks posed by climate change and other environmental challenges. Models like DAHiTrA, Long Short-Term Memory (LSTM) Networks, Hydrological Simulation Models based on Artificial Intelligence, and GloFAS, show increased accuracy in predicting extreme natural events. It has been demonstrated that these forecasts based on artificial intelligence outperformed traditional models. Organizations like the UN and UNESCO are working to ensure early warning systems are available to all by 2027.

The machine learning models and approaches used to enhance flood forecasting and disaster management mentioned in the article are the following:

1. <u>Damage Assessment from High-Resolution Imagery Through AI (DAHiTrA) Deep Learning Model</u>
   This model uses Convolutional Neural Networks (CNN), which is a type of deep learning model that specializes in analyzing visual data, like satellite images. The model compares the satellite images taken before and after a disaster (such as floods or earthquakes) to detect changes in infrastructure, buildings, roads, and bridges, helping authorities determine the number of affected buildings quickly after an event. It assesses the damage levels and helps determine which areas are a priority for relief efforts.

[30] Della Mura, M. T. (2024, April, 29). *Early warning systems: harnessing AI to mitigate risks*. TECH4FUTURE. https://tech4future.info/en/early-warning-systems-ai/

The process can be summarized in the following way:

- **Pre-disaster Image**: DAHiTrA analyzes high-resolution satellite images of the affected area before the disaster.
- **Post-disaster Image**: After the disaster, new satellite images are analyzed and compared with pre-disaster images.
- **Damage Classification**: The model classifies the level of damage using image recognition techniques by identifying changes in structural features, debris, or destruction.

Kaur, N., Lee, C.-C., Mostafavi, A., & Mahdavi-Amiri, A. (2023) in their article titled "*Large-scale building damage assessment using a novel hierarchical transformer architecture on satellite images*", introduced DAHiTrA, to classify building damages based on satellite images in the aftermath of natural disasters. They compared their model to others to see how it performed and made the following statement regarding the image below:

"Additional figures for qualitative results for damage classification (evaluation on the xBD data set), containing images from hard terrains, images with poor quality, and rural regions. As observed in the figure, the model performs well on these images as compared to other baselines. The last row contains zoomed in results from imagery with moving objects like vehicles. The models effectively ignore such objects while identifying the building structures."[31]

[32] Kaur, N., Lee, C.-C., Mostafavi, A., & Mahdavi-Amiri, A. (2023). Large-scale building damage assessment using a novel hierarchical transformer architecture on satellite images. Computer-Aided Civil and Infrastructure Engineering, 38, 2072–2091. https://doi.org/10.1111/mice.12981

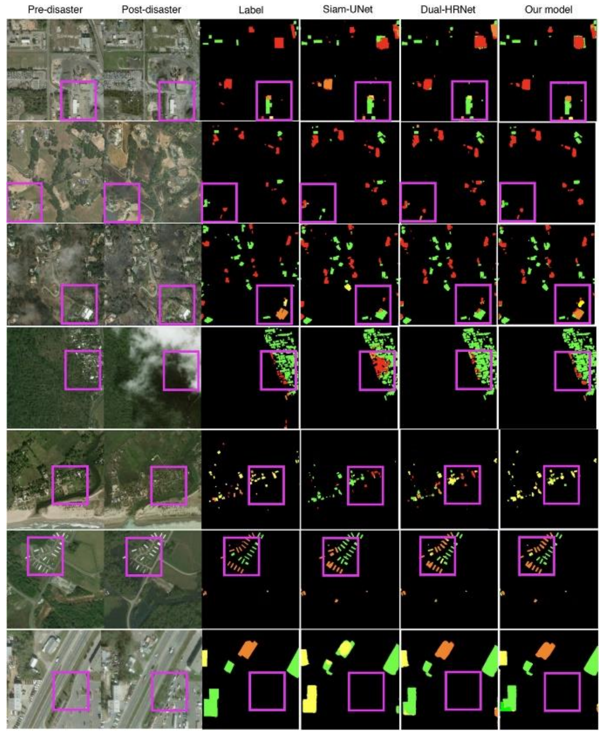

Figure 5.1: Comparison of the DAHiTrA model (their model)[32]far right, with other models[32]

2. Long Short-Term Memory (LSTM) Networks

   It is a type of recurrent neural network (RNN) designed to handle sequential or time-series data. They are particularly effective in cases where data involves dependencies over time. In the context of flood prediction, LSTM networks were applied to forecast daily river flow across a seven-day horizon. This model was trained and tested using data from flow measurement stations, and it did well when it came to the prediction of extreme hydrological events.

   The process can be summarized in the following way:

   - **Memory Cells**: LSTMs have a unique architecture with memory cells that allow them to retain information over long sequences, making them well-suited for forecasting time-dependent processes.
   - **Input**: Historical river flow data from monitored stations is fed into the network, including variables like rainfall, temperature, and soil moisture.
   - **Prediction**: The LSTM uses past data to predict future values; in this case, river flow levels over the next seven days.

[32] *Id.*

- **Training and Testing**: The model is trained using k-fold cross-validation, where data is split into several parts, also known as folds, and the model is tested on different portions of the data to ensure accuracy.

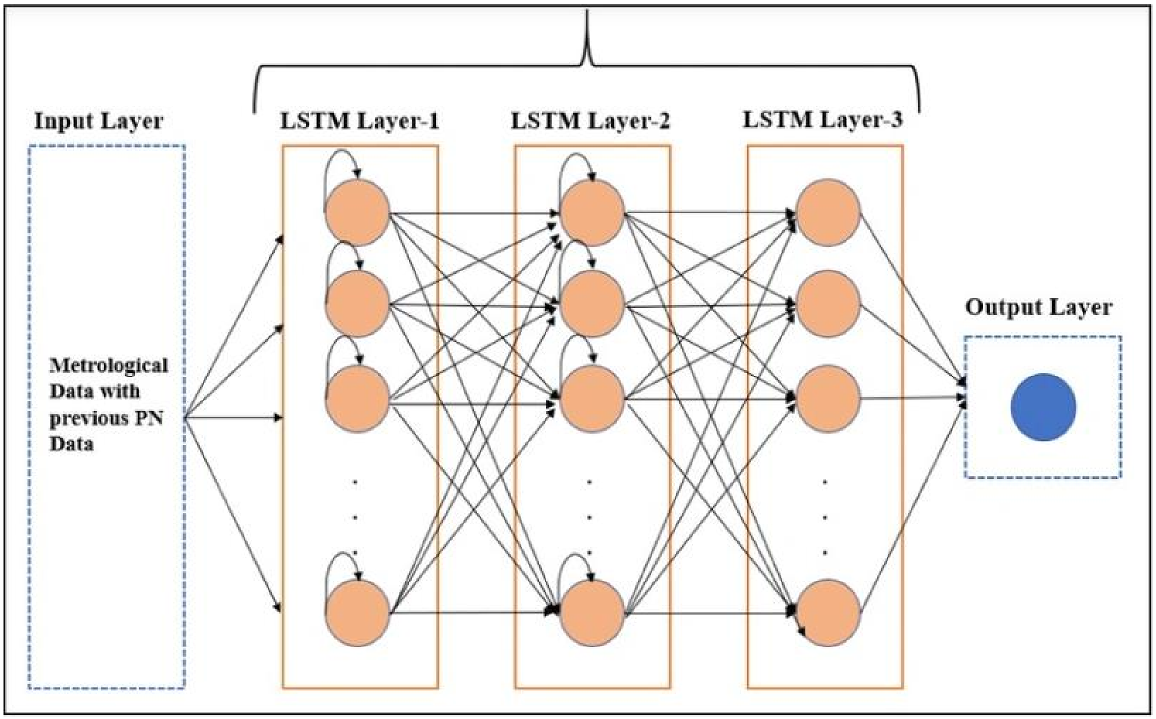

Figure 5.2: Schematic of LSTM Networks[33]

3. Hydrological Simulation Models based on Artificial Intelligence

These models were developed for river basins where there is almost no direct measurement of hydrological data, particularly river flow or discharge, and regions lacking monitoring data like water levels, flow rates, and other critical parameters. They utilized machine learning to provide large-scale, precise river flow predictions, focusing primarily on extreme events. These models enable flood forecasting in areas where traditional hydrological models struggle due to a lack of historical data.

The process is the following:

- **Data Collection**: These models rely on publicly available data, such as global precipitation maps, elevation models, and remote sensing data.
- **Training**: The model is trained on regions with known river flow data, learning how environmental factors correlate with river flow.

[33] Emerging India Group. (2024, May, 23). Understanding Long Short Term Memory (LSTM) Networks. Emerging India Analytics. https://emergingindiagroup.com/long-short-term-memory-lstm/

- **Transfer Learning**: Once trained, the model is applied to ungauged basins, using input data like rainfall patterns and topography to estimate river flow in those unmonitored regions.

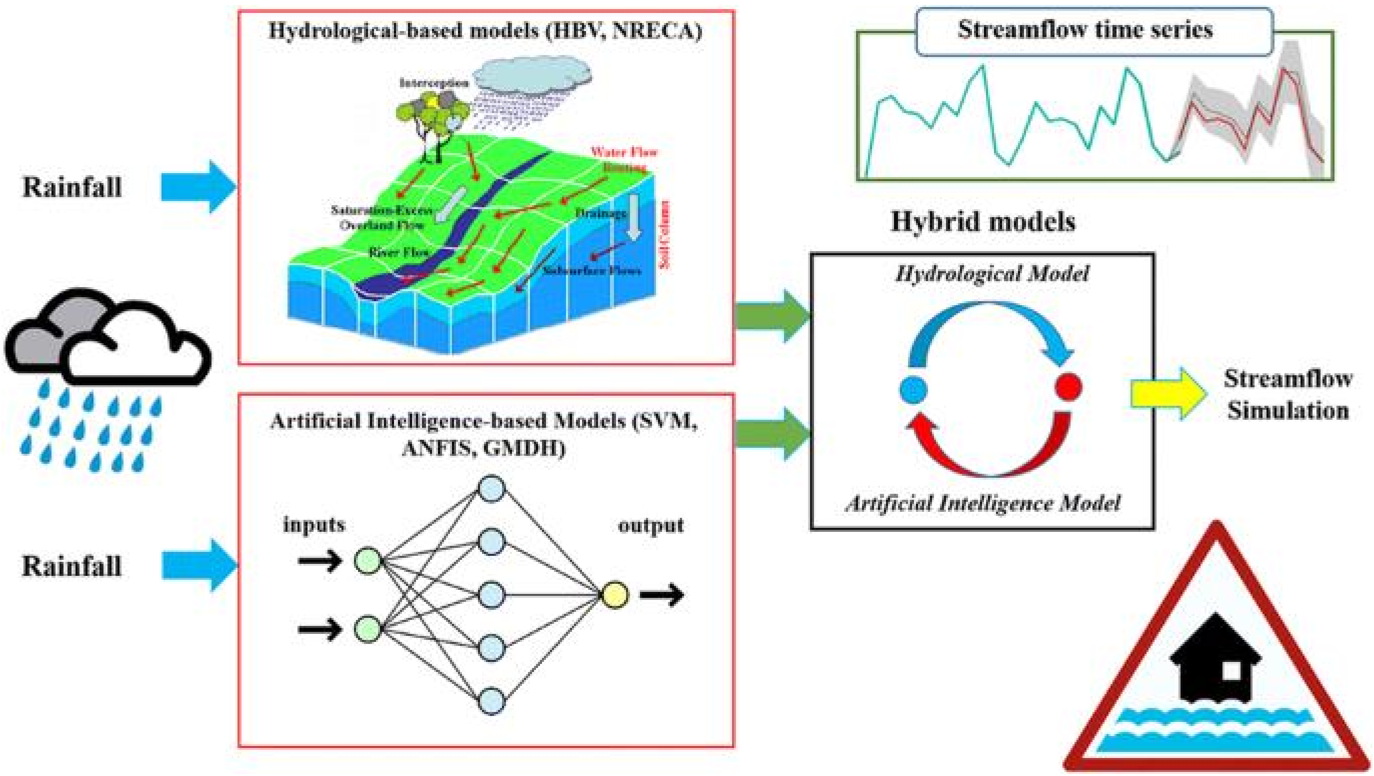

Figure 5.3: Example of a hydrological simulation model based on artificial intelligence[34]

4. <u>Global Flood Awareness System (GloFAS)</u>

GloFAS is used by governments and disaster management agencies to issue flood warnings and coordinate emergency response, with the ability to forecast extreme events several days in advance. It is a system that integrates meteorological data, hydrological models, and forecasts made by AI to provide real-time flood prediction on a global scale. It combines numerical weather predictions from the European Centre for Medium Range Weather Forecasts (ECMWF) with river discharge models.

The way it works is described below:

- **Weather Forecasting**: GloFAS uses weather forecasts, like rainfall predictions and temperature, to simulate how these conditions will affect river flows.
- **Hydrological Modeling**: A hydrological model simulates the flow of water through river systems based on incoming precipitation, topography, and land cover.
- **AI-Enhanced Forecasting**: AI algorithms are used to improve the accuracy of flood forecasts by analyzing past flood data and adjusting the model to better predict future events.

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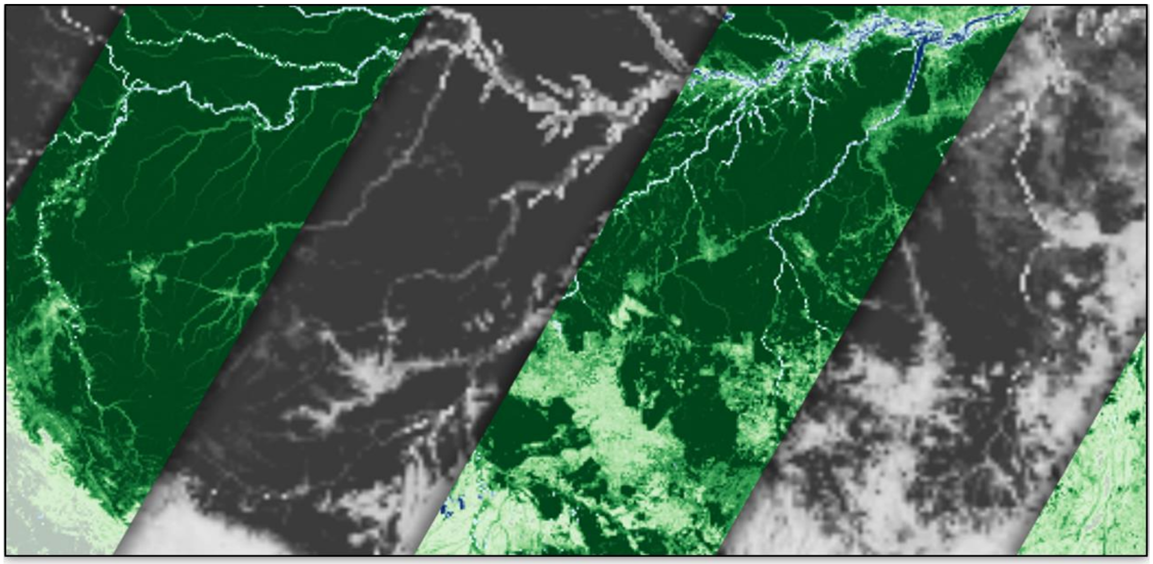
[34] Mohammadi, B., Moazenzadeh, R., Christian, K. et al. (2021) *Improving streamflow simulation by combining hydrological process-driven and artificial intelligence-based models*. Environ Sci Pollut Res 28, 65752–65768. https://doi.org/10.1007/s11356-021-15563-1

- **Benchmarking**: The system combines data from both monitored and unmonitored sites to provide flood risk assessments and early warnings globally, especially in areas where traditional data collection is scarce.



Comparison of the forest fraction map as used in the hydrological model OS LISFLOOD for GloFAS at 0.05 (green) and 0.1 (grey) degree.

Figure 5.4: Comparison of the forest fraction map as used in the hydrological model OS LISFLOOD for GloFAS at 0.05 (green) and 0.1 (grey) degree[35]

These models highlight how AI and machine learning can analyze vast amounts of environmental data, forecast extreme events, and improve decision-making during disasters, particularly in flood-prone regions.

In the case of energy prices, Muneer M. Alshater, Ilias Kampouris, Hazem Marashdeh, Osama Atayah, and Hasanul Banna, in their 2022 article *Early warning system to predict energy prices: the role of artificial intelligence and machine learning*[36], they tested the effectiveness of EWS in predicting energy prices during the pandemic, evaluating uncertainty risk during COVID-19 in the USA using uncertainty indices and energy equity indices, comparing ML models with conventional approaches, and showcasing the superiority of ML in accurate price forecasting.

In late 2019, the COVID-19 pandemic caused significant disruptions, leading to increased unemployment and economic slowdown. The global energy system saw a drop in consumption and uncertainty about supply and consumption patterns. Lockdown measures restricted human mobility and manufacturing activity, resulting in

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[35] Gremaldi, S. (2023, July, 5). *Copernicus Emergency Management Service GloFAS update: pre-release of version 4.0 is now available*. Copernicus, Europe's eyes on the Earth. Emergency Management System. https://global-flood.emergency.copernicus.eu/news/140-copernicus-emergency-management-service-glofas-update-pre-release-of-version-40-is-now-available/

[36] Alshater, M.M., Kampouris, I., Marashdeh, H. et al. (2022, August 22). *Early warning system to predict energy prices: the role of artificial intelligence and machine learning*. Ann Oper Res https://doi.org/10.1007/s10479-022-04908-9

decreased energy demand. This shock caused a sharp decline in energy equities prices, especially in the US market, where crude oil futures prices turned negative for the first time in history.

The volatility of energy commodities, especially crude oil, had devastating effects as they are crucial for the global economy. The Russian invasion of Ukraine further increased market volatility. This economic disturbance raised concerns among investors globally, prompting a need to mitigate its negative effects. The study aims to examine key aspects of the US energy equity markets during uncertain economic conditions, like the pandemic and the beginning of the Russian – Ukrainian War.

Their study focused on predicting energy prices using uncertainty indices, comparing conventional methods with machine learning approaches, and determining the most effective Early Warning System (EWS) for the energy sector. Machine Learning is highlighted as a reliable tool for addressing complex tasks that conventional methods may struggle with. ML models offer better data processing, allowing for accurate prediction of energy prices and helping control costs, identify market trends, and inform policymakers and regulators.

In the US, the energy system relies on a vast interconnected network that generates and distributes energy from various sources to meet growing demand. External factors like crises, natural disasters, and economic uncertainty impact energy stock prices and volatility. To navigate these challenges, understanding the link between energy prices and external factors is essential for investors and policymakers in crisis situations.

Traditional methods, like regression, have been used to predict stock price volatility, but in recent years, machine learning and artificial intelligence have emerged as alternative approaches. Machine learning can identify data patterns and improve effectiveness over time, this has already been applied to various fields, including energy economics, to forecast electricity prices.

Researchers have used methods like Artificial Neural Networks (ANN) and Support Vector Machines (SVM) to predict power prices with a high degree of accuracy. Combining machine learning with econometric models has also gained traction, with models like Non-Linear Autoregressive models and Generalized Autoregressive Conditional Heteroskedasticity used to forecast crude oil prices. These models have shown promise in managing input factors like demand, supply, and market indices.

Deep Learning models, like Stacked Denoising Autoencoders and Adaptive Multiscale Ensemble Learning, have shown potential in predicting complex time series data and improving accuracy in forecasting crude oil prices. Ensemble methods, like Extended Extreme Learning Machine and Complementary Ensemble Empirical Mode Decomposition, have also been successful in enhancing predictive accuracy for petroleum prices.

The data used for the study done by Alshater and the other authors consisted of observations made from January 1, 2011, to January 18, 2022, comprising a total of 2677 observations using Thomson Reuters DataStream as its source. The dataset includes two types of indices:

A. Energy Equity Indices (Panel A):

- US Renewable Energy Equity Index
- US Oil, Gas, and Coal Equity Index
- US Pipelines Equity Index
- US Oil Equity & Services Index
- US Oil & Gas Refining & Marketing Equity Index
- US Oil: Crude Production Equity Index
- US International Oil & Gas Index
- Main US Energy Index

US energy equity indices are listed here in Panel A. The energy indices had higher volatility, particularly the US Oil & Gas Refining & Marketing Equity Index, while the US Renewable Energy and US Pipelines had the lowest volatility. Most indices are skewed with lower kurtosis than 3.

B. Economic Uncertainty Indices (Panel B):

- Twitter Economic Uncertainty Index (TEU-USA)
- EMV Infections Uncertainty Index
- Economic Policy Uncertainty Index (EPU)
- CBOE Market Volatility Index (VIX)

Economic uncertainty indices are in Panel B. TEU-USA and EPU have the highest volatility, while VIX has the lowest volatility with all uncertainty indices being positively skewed, right-skewed, and showing high kurtosis.

At the same time, the study divided the dataset into two periods:

- Pre-pandemic period: January 6, 2011, to December 31, 2019.
- COVID-19 pandemic period: January 1, 2020, to January 18, 2022.

Three important COVID-19 related dates are highlighted: January 27, 2020 (WHO global threat declaration), February 24, 2020 (rise in cases outside China and market collapse), and September 3, 2020 (global lockdown).

Alshater and the other authors use machine learning (ML) and traditional approaches, like regression, to predict energy equity indices prices. The Root Mean Square Error (RMSE) is used to assess the accuracy of the models. Previous studies have combined ML approaches with conventional models to make predictions, but this study combines various ML models with Multiple Linear Regression (MLR) to forecast energy prices pre- and during the COVID-19 pandemic. The study aims to evaluate the impact of economic uncertainty indices on energy economics and finance during the pandemic, considering the significant fluctuations in energy demand. The MLR method is chosen due to its suitability for the model structure and variables. The methodology was the following:

1. <u>Multiple Linear Regression</u>

   MLR is applied to test the relationship between uncertainty indices and energy prices. It is used as the baseline model for comparison with the ML models.
2. <u>Machine Learning Models</u>

   The study employed a wide variety of Supervised Regression-based ML models, including:
   - Generalized Linear Models (GLM)
   - Support Vector Machines (SVM)
   - Regression Trees
   - Gaussian Process Regression (GPR)
   - Neural Networks (NN), including the Levenberg–Marquardt algorithm for training NN.
3. <u>Performance Evaluation</u>

   The Root Mean Square Error (RMSE) and R-squared are the key metrics used to assess the accuracy of each model. The models are trained and evaluated in both the pre-pandemic and pandemic periods to assess their performance in times of crisis, in this case the pandemic.

Their study also incorporated Deep Learning methods to train networks for dynamic time series analysis, specifically, the Levenberg—Marquardt algorithm.

Their results discussed the fact that the Multiple Linear Regression model shows low predictive power during the pre-pandemic period, with low R-squared values across all indices. However, during the pandemic, the performance of the model improves, with R-squared values ranging from 0.44 to 0.67 for different indices. The highlights of their study are:

- Higher uncertainty leads to lower energy prices, this is because most uncertainty indices are negatively correlated with energy prices.
- The Economic Policy Uncertainty (EPU) and Twitter Economic Uncertainty (TEU-USA) indices are the variables that affect the most in most cases.
- The CBOE Volatility Index (VIX) is negatively correlated but not statistically significant for some indices.
- The Machine Learning models consistently outperform Multiple Linear Regression in both pre-pandemic and pandemic periods.

The Machine Learning models performed way better than the Multiple Linear Regression when it came to predictive power. Neural Networks (NN) with the Levenberg–Marquardt algorithm delivered the best results, with significantly lower RMSE and higher R-squared values (as a reminder the lower the RMSE and the higher the R-squared value, the more accurate the model). Gaussian Process Regression (GPR) models and Regression Trees also performed well but were slightly less accurate than NN. The Support Vector Machines (SVM) rank third and fourth, showing lower performance than NN and GPR but still outperforming MLR. Traditional models, like MLR, sometimes struggle to capture the complexities and volatility of energy prices during crises, while ML models, with their ability to handle large, non-linear datasets, are better suited for these conditions.

Neural Networks trained with the Levenberg–Marquardt algorithm, provide the most accurate predictions due to their ability to model non-linear relationships and complex interactions between multiple variables, and can also efficiently handle large datasets with dynamic inputs.

Their study concluded that the models perform better during the pandemic than in the pre-pandemic period. This could be because increased uncertainty during the pandemic provided stronger signals for the models to capture price movements. The inclusion of uncertainty indices as predictors enhances the ability of the models to capture market sentiment and predict energy price fluctuations. The Economic Policy Uncertainty (EPU) and Twitter Economic Uncertainty (TEU-USA) indices are particularly effective in explaining energy price volatility. Machine Learning and AI models offer superior predictive power over conventional models like Multiple Linear Regression in forecasting energy price volatility, especially during crises such as the COVID-19 pandemic. Neural Networks, with the Levenberg–Marquardt algorithm, are the most accurate model for predicting energy equity prices, providing the best balance between RMSE and R-squared. Machine Learning models outperform traditional econometric models in both stable and volatile market conditions, this process that they are more adaptable to the uncertainty brought by external shocks like the pandemic or geopolitical conflicts like Russian – Ukrainian War.

Lastly, the study made by Alshater, Kampouris, Marashdeh, highlights the importance of integrating AI and ML into Early Warning Systems (EWS) for energy markets. Such systems can help policymakers, investors, and market regulators make more informed decisions, leading to better market stabilization, risk management, and resource allocation. At the same time, ML models can improve energy market efficiency by offering timely and accurate predictions, contributing to the overall resilience of the global energy sector.

For more information on how machine learning is being implemented to predict oil prices and how the model developed by Alshater, Kampouris, Marashdeh, Osama, and Banna, works, please consult their article *Early warning system to predict energy prices: the role of artificial intelligence and machine learning*.

Chapter VI: Applications of Artificial Intelligence in Early Warning Systems for Energy

As has been discussed in previous chapters, energy systems are becoming more complex and interconnected, and because of this, it is crucial that EWS can detect anomalies throughout the entire system, it is here where AI using machine learning algorithms can aid EWS. AI, through machine learning algorithms and real-time data analytics can give its users solutions that can enhance the detection, analysis, and response to energy disruptions, improving the reliability and efficiency of energy systems. Large Language Models (LLM), which is a type of machine learning model, is being integrated into early warning systems for energy systems, to enhance the prediction and response ability of EWS to potential disruptions, improving the reliability, safety, and efficiency of energy systems.

The NYU Libraries (2024) give the following definition of what Large Language Models are, how they are trained, and how they work:

> *"Large Language Models (LLMs) refer to large general-purpose language models that can be pre-trained and then fine-tuned for specific purposes. They are trained to solve common language problems, such as text classification, question answering, document summarization, and text generation. The models can then be adapted to solve specific problems in different fields using a relatively small size of field datasets via fine-tuning.*
>
> *The ability of LLMs taking the knowledge learnt from one task and applying it to another task is enabled by transfer learning. Pre-training is the dominant approach to transfer learning in deep learning.*
>
> *LLMs predict the probabilities of next word (token), given an input string of text, based on the statistical properties of the language in the training data. Typical training corpora for LLMs include natural language (e.g. web data). But LLMs can also be trained on other types of languages (e.g. programming languages).*
>
> *LLMs are large, not only because of their large size of training data, but also their large number of parameters. They display different behaviors from smaller models and have important implications for those who develop and use A.I. systems."*[37]

[37] NYU Libraries. (2024, September 7). *Machines and Society, What Large Language Models Are.* NYU Libraries. https://guides.nyu.edu/c.php?g=1308742&p=9997824

The most well-known example of what a Large Language Model is, is Chat GPT which was developed by Open AI.

Large Language Models enhance data accessibility by providing user-friendly interfaces where users can ask any kind of question they might have. Since all kinds of questions can be asked, the model can help stakeholders make more informed decisions across various levels of an organization. For example, energy systems have to meet many standards regarding regulations, and Large Language Models can assist in the monitoring by making sure that the systems comply with all policies by analyzing legal documents and regulatory changes. They can identify relevant requirements and flag potential compliance issues before they escalate into significant risks for organizations operating within the energy sector. This capability allows energy operators to stay informed about emerging threats or changes in regulations that could impact operations.

Large Language Models can also assist in predictive maintenance by analyzing historical maintenance records, equipment manuals, and operational data. This is done through the identification of patterns that precede equipment failures, and the model can help predict when maintenance is needed, thereby reducing unplanned outages and improving system reliability, while also maintaining the integrity of large energy infrastructures.

In the case of an emergency that affects energy systems, like natural disasters or a cyberattack, Large Language Models can assist in the response coordination by analyzing real-time data from multiple sources. The models can identify high-risk scenarios and provide early warnings about potential disruptions due to extreme weather events or system failures. They can help identify affected areas, assess damage, and recommend immediate actions based on previous incident responses, since they were trained with this kind of information, improving overall energy system resilience.

Although it seems like Large Language Models are the way to go, they do have some limitations, as Rebecca Lake (2024) says:

> *"The quality of the content that an LLM generates depends largely on how well it's trained and the information that it's using to learn. If a large language model has key knowledge gaps in a specific area, then any answers it provides to prompts may include errors or lack critical information.*
>
> *Large language models primarily face challenges related to data risks, including the quality of the data that they use to learn. Biases are another potential challenge, as they can be present within the datasets that LLMs use to learn. When the dataset that's used for training is biased, that can*

then result in a large language model generating and amplifying equally biased, inaccurate, or unfair responses."[38]

Large Language Models are only as good as the information it is given to train with. If the information that is being used comes from unreliable sources or is incomplete, the answers provided by the model will surely be incorrect. Therefore, it is important for the creators of the model to teach it to discard information that is not fact checked or that is false as this can be incredibly dangerous and could confuse threats with normal situations, giving way to probable collapse of the entire energy system.

This chapter will explore the various applications of AI in EWS for energy-related anomalies, management and the operations of energy systems, energy grids, carbon capture utilization and storage (CCUS), oil and gas exploration and drilling, and geopolitical risks.

Applications of AI in Early Warning Systems for Energy-Related Anomalies

AI algorithms, and especially those based on machine learning, can analyze large amounts of real-time data gathered from smart meters, and sensors; like the Stacked Denoising Autoencoders and Adaptive Multiscale Ensemble Learning, discussed in the previous chapter which are used to predict complex time series data and improve the accuracy in forecasting crude oil prices. The AI model is given energy consumption patterns that it uses to train, these patterns work as a standard and it is constantly collecting data to compare it to its given pattern to identify anomalies such as unexpected spikes or drops in energy usage. This anomaly detection improves the reliability of the energy grid by providing utility service companies with insights into operational inefficiencies, and then they can take the appropriate actions before problems grow out of proportion. For example, if a meter shows a significant increase in consumption when it is not typically a period of high consumption, the system flags this as a potential issue, which would then lead to further investigation into what possible causes could be, for example equipment malfunction or somebody placing a breaker to redirect energy.

Yassine Himeur, Khalida Ghanem, Abdullah Alsalemi, Faycal Bensaali, and Abbes Amira (2021) made the following statement regarding supervised anomaly detection through machine learning:

> *"Supervised anomaly detection in energy consumption necessitates training the machine learning classifiers (binary or multi-class) using annotated datasets, where both normal and abnormal power consumption is labeled. Although supervised anomaly detection can achieve high-accuracy*

[38] Lake, R. (2024, August 20). *What is a Large Language Model?* Investopedia. Business. Products and Services. https://www.investopedia.com/large-language-model-7563532#toc-limitations-of-large-language-models

identification results as demonstrated in academic frameworks, its adoption in the real world is still limited compared to unsupervised methods, due to the absence of power consumption annotated datasets."[39]

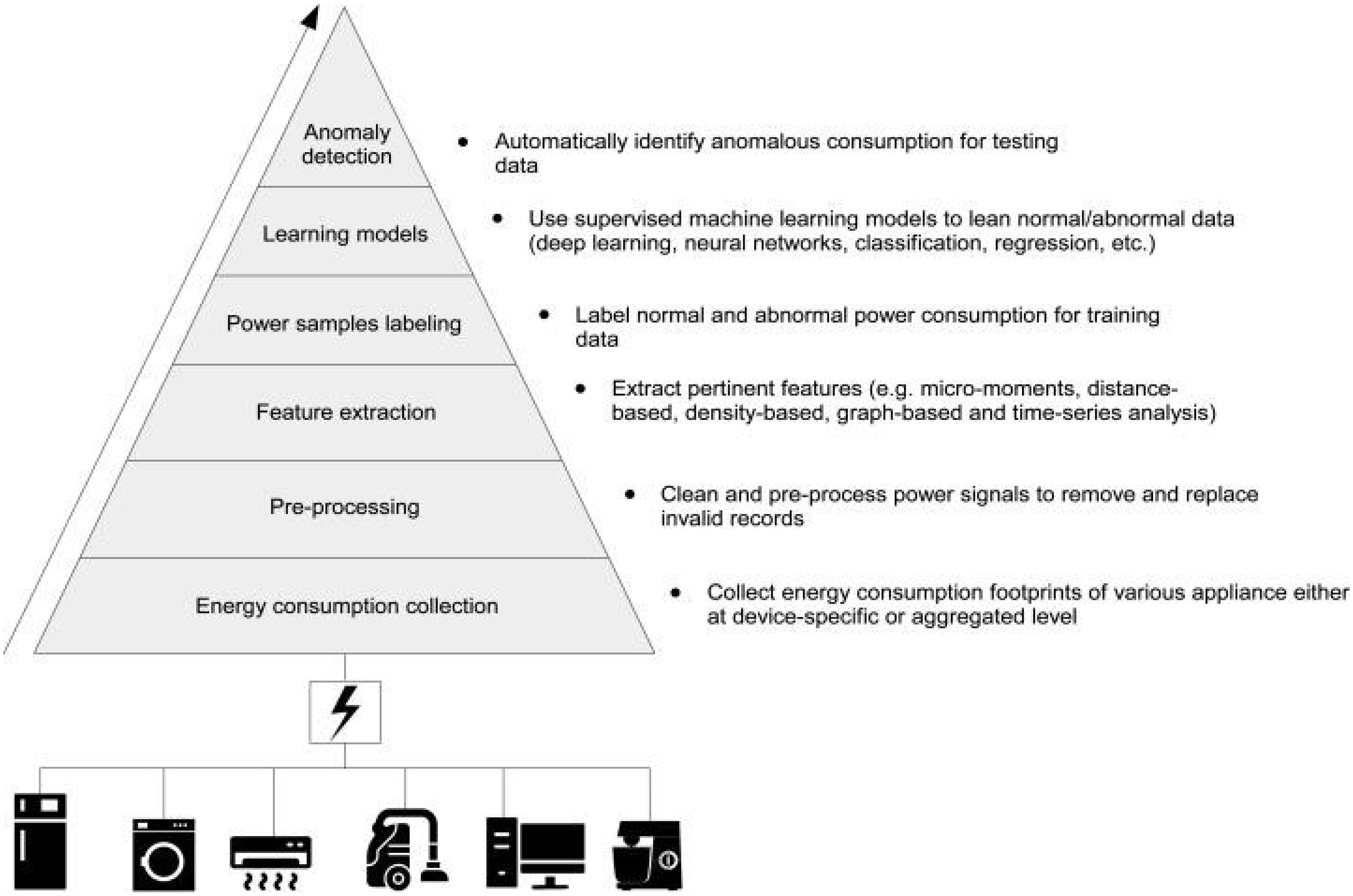

Figure 6.1: The main steps used to perform a supervised anomaly detection of energy consumption in buildings[40]

As energy systems evolve and new patterns emerge, AI models have to adapt by updating their algorithms based on the new information that is being collected, it is a constant training and practicing process. This continuous learning process improves the accuracy of anomaly detection systems, allowing them to remain effective even if operational conditions change, and as part of this continuous learning process, the algorithms have to learn that energy systems are becoming more and more connected with smart technologies, and because of this connection, energy grids also become more vulnerable to cybersecurity threats. Therefore, it is crucial that there is a good

[39] Yassine H., Khalida G., Abdullah A., Faycal B., Abbes A., (2021). *Artificial intelligence based anomaly detection of energy consumption in buildings: A review, current trends and new perspectives*. Applied Energy. Volume 287. 2021. 116601. ISSN: 0306-2619. https://doi.org/10.1016/j.apenergy.2021.116601. https://www.sciencedirect.com/science/article/pii/S0306261921001409
[40] *Id.*

integration of the AI algorithm with cybersecurity measures that enhance the resilience of energy infrastructures by giving them the ability to monitor in real-time the network traffic allowing the algorithm to scan for unusual patterns which could be potential security breaches. Machine learning algorithms can analyze user behavior and detect anomalies, like unauthorized access or attacks on critical systems, and if the algorithms identify these threats early, organizations can deploy countermeasures to protect their assets. An AI model that was trained on historical consumption data will need to keep updating itself as new technologies like electric vehicles as they become more and more present in energy grids, and the AI algorithm has to think and understand how can these new things bring new cybersecurity threats into the grid.

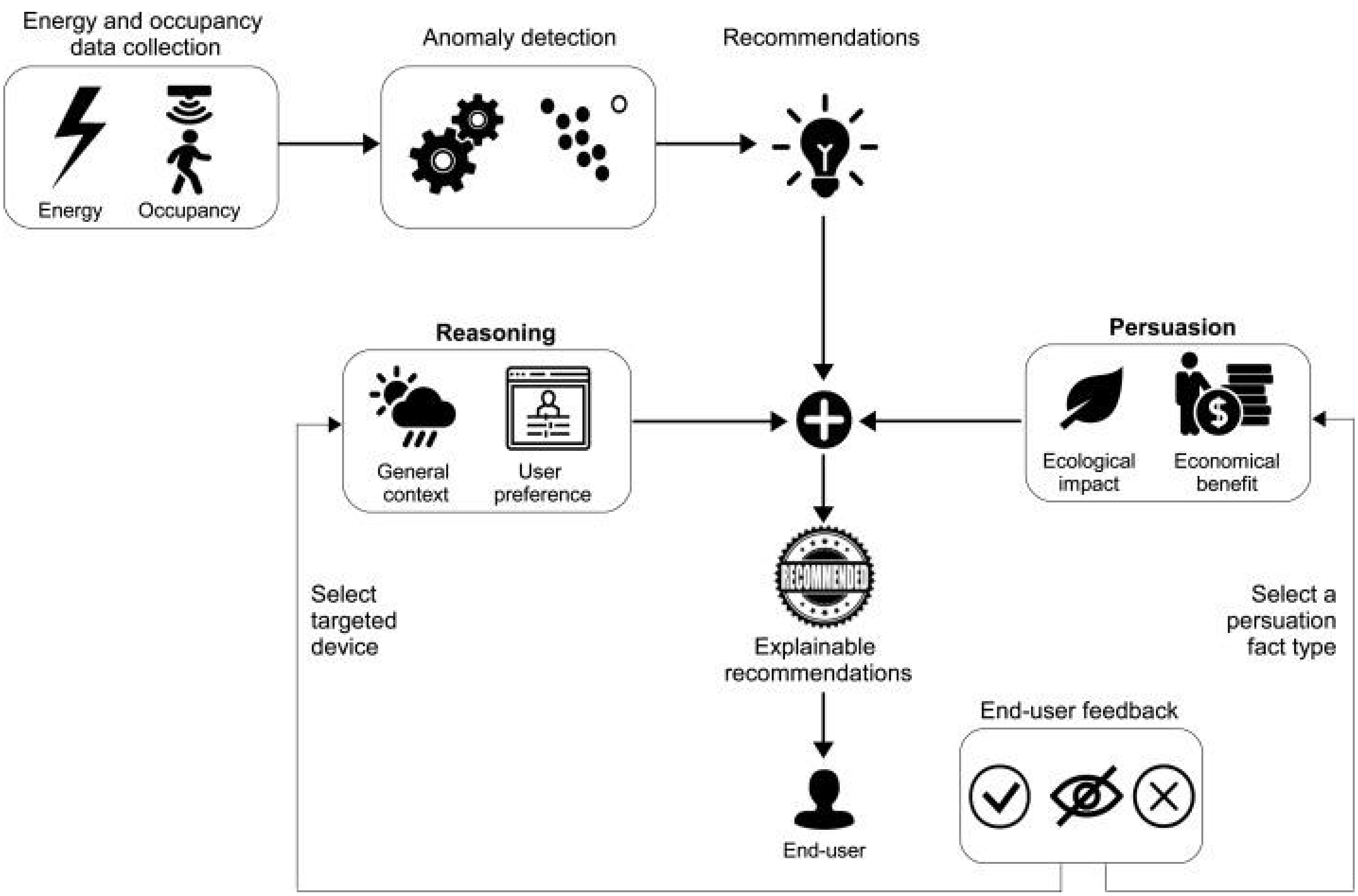

Figure: 6.2: Example of the flowchart of an energy saving system based on the combination of anomaly detection and RS, in which the output of the anomaly detection module serves as an input for the RS to help end-users in correcting their energy consumption behaviors.[41]

Applications of AI in Early Warning Systems for the Management and Operations of Energy Systems

[41] *Id.*

AI algorithms are also being used to predict when maintenance is due through the analysis of performance history data and operational data that it was trained with and the patterns that it discovers before a piece of equipment had a malfunction, it uses it as a standard and from there it can prevent equipment malfunction because it can forecast when equipment will fail. AI algorithms learn and identify the subtle patterns that precede failures through the use of machine learning techniques, like regression analysis and neural networks, and this gives operators the ability to schedule maintenance before a breakdown occurs, since the algorithm has identified a pattern, that equipment might fail if maintenance is not given to it. The advantages of this use of AI algorithms are the minimization of the downtime of the piece of equipment that requires maintenance, a reduction of maintenance costs and extends the lifespan of infrastructure.

AI is also very good at processing and analyzing large datasets from various sources, including weather data, historical consumption records, and real-time operational data, this gives organizations deeper knowledge into energy consumption behaviors and trends. The scanning and analysis of different datasets is done using clustering and classification techniques, and by using these techniques it can identify patterns that may not be apparent through traditional analysis methods. The patterns found by the AI model give energy providers an idea of how to improve their resource allocation, demand forecasting, and it lets them perform efficient simulations. The ability of AI to simulate various operational scenarios is crucial to prepare organizations for potential disruptions in energy systems and it helps them understand the impacts of various anomalies, rethink and refine their response protocols.

AI algorithms can predict consumption patterns based on historic and real-time data to enable utilities to turn off on their own when they are not in use. AI algorithms will monitor and control the flow of electricity during sudden peaks in demand and channel the power to where it will be most needed to prevent any kind of power surge or even a blackout. Smart electrical grids with inbuilt AI can track a fault or disturbance due to malfunctioning machinery or outage and can pinpoint exactly where the problem is located by using algorithms based on AI and can then reroute the power to cut service interruptions, reduce downtime, and make the grid much more reliable.

Applications of AI in Early Warning Systems in Energy Grids

An electrical grid or power grid, is an interconnected network that facilitates the generation, transmission, and distribution of electricity from producers to consumers. This system is essential for delivering electricity across the land and sea, ensuring that homes, businesses, and industries have access to this energy.

A smart energy grid is an energy grid that integrates information and communication technologies to enhance the efficiency, reliability, and sustainability of electricity distribution. Unlike traditional grids, which operate on a one-way communication model from producers to consumers, smart grids use two-way communication, allowing real-time feedback provided by consumers by using their utilities to the manufacturers and the energy providers. One key aspect of smart grids is that they are designed with the intent of increasing the integration of renewable energy sources, like solar and wind, which can vary a lot as was discussed in previous chapter 2. This capability helps optimize energy use during peak demand periods and reduce energy waste.

Large Language Models are also being applied here, since they can enhance the functionality of smart grids by improving demand forecasting and resource allocation, similar to what has already been discussed. Once again, these models analyze real-time data coming from various sources, including user inputs, weather forecasts and consumption patterns, and they help optimize energy distribution and they manage the energy load management. This application is geared more towards the implementation of renewable energy sources into the energy grid. Another aspect to consider regarding this implementation is the security of the grid because the models can analyze social media posts and communications to identify potential security threats to energy infrastructure, once the pattern has been detected Large Language Models can provide a quicker response and deploy the appropriate actions to mitigate or neutralize the cybersecurity breach. The models can make communication within energy organizations a lot easier by generating clear and concise reports on system status, incidents, and regulatory compliance. Meeting summaries or incident reports can be made quickly and clearly to ensure that stakeholders have quick access to vital information during emergencies.

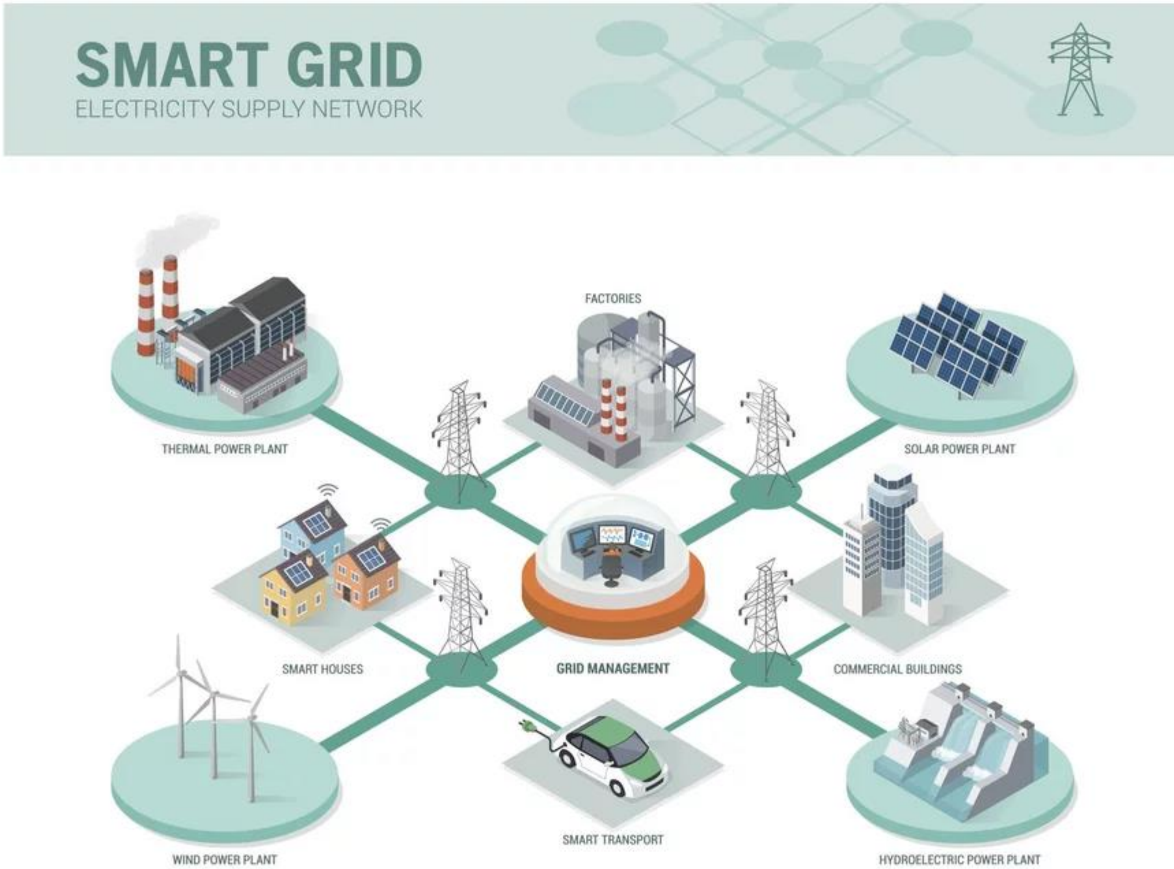

Figure 6.3: Schematic of a smart grid[42]

Applications of AI in Early Warning Systems for Carbon Capture Utilization and Storage

The Consultancy Services Team of FDM (2023) created a list of the top 10 uses for AI in the energy sector and regarding Carbon Capture Utilization and Storage they made the following statement:

> *"AI enhances the efficiency of CCUS processes by optimising the capture of carbon dioxide from the atmosphere or emission sources. AI-driven systems can identify the most suitable methods for utilising captured carbon, whether for industrial processes or safe long-term storage. This technology plays a vital role in reducing greenhouse gas emissions and mitigating climate change."*[43]

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[42] Horner, M. (2022, February 21). *Top 10 applications of AI and Robotics in Energy Sector*. Energy Digital. Technology & AI. https://energydigital.com/top10/top-10-applications-of-AI-and-Robotics-in-Energy-Sector

[43] Consultancy Services Team of FDM. (2023, March 22). *Top 10 applications of AI in the energy sector*. FDM Group. Insights for Organizations. https://www.fdmgroup.com/news-insights/ai-in-energy-sector/

As has been noticed, Large Language Models are also the Machine Learning model employed here to aid in the early detection, or compromise of the reservoir, or capture and injection facilities. Carbon dioxide is retrieved from industries such as the cement manufacturing, steelmaking, chemical producing facilities, these industries, along with the aviation industry are considered hard-to-abate, meaning that it is difficult for them to lower their greenhouse gas emissions; which in turn makes them the ideal target to capture carbon dioxide from. Once captured, the CO_2 is compressed into a supercritical fluid to reduce its volume as much as possible for transportation via pipelines, trucks, or ships to utilization sites or storage locations. Once it reaches its destination it is either injected into a depleted oil and gas reservoir, or it is used as fuel for chemical production. At any of these points AI, through the data it was given to train with can detect patterns and emit an early warning for any situation that it considers as a risk, this could be in the form of a detection that the gas not compressed adequately or an equipment malfunction.

Applications of AI in Early Warning Systems in Oil and Gas Exploration and Drilling

The role of AI in this scenario of oil and gas exploration is a bit different than what could be expected since its use has been more of an alert that there are indicators that a negative situation might unfold and that stakeholders, governments, companies, and general users should take appropriate countermeasures to mitigate or completely avoid a harmful situation. For this case, AI through the use of Large Language Models using geological and seismic data can identify potential oil and gas reserves that may have gone previously unnoticed using traditional methods, and at the same time assessing the viability of these reserves, guiding exploration efforts toward the most promising prospects. In this case the early warning system is oriented more towards the risk of missing out on potential hydrocarbon reserves, this increases the chances of finding prospective reservoirs while at the same time reducing wasted time and money.

For the case of drilling operations, the early warning system functions as it has been described in previous applications since there are many factors, components, fluids, and machinery at play. A misfunction could lead to a failure of the drilling operation or, in the worst case scenario, lives lost as it happened in 2010 with the Deepwater Horizon oil rig off the coast of Louisiana in the Gulf of Mexico. Once more, the Consultancy Services Team of FDM, now highlights the use of AI in drilling operations:

> *"AI-driven predictive models assess various factors, including geological formations, drilling equipment performance, and environmental conditions, to anticipate potential risks and challenges. By doing so, AI empowers drilling teams to proactively address issues, enhance safety measures,*

and optimise drilling processes, resulting in safer and more productive operations in the oil and gas industry."[44]

During drilling operations, engineers have to ensure that the integrity of the well and the formation is never compromised. The process of drilling a well consists of many stages, which have many variables at play.

After the engineers and supervisors have looked at all the geological and seismic data, and have drawn their conclusions that a certain geographical area could prospectively contain hydrocarbons in the subsurface, they will start developing drilling plan where they will define the depth of interest, what type of drill bit shall be used, what kind of drilling mud will be run throughout the drilling process and at what depths will the casings be placed until the prospective production interval is reached.

Before drilling operations begin, the drilling mud must be prepared. Some of the functions of the drilling mud are:

- ❖ Lubrication of the drill bit and cooling of it to prevent overheating
- ❖ The density of the mud must be sufficient to prevent the well from collapsing in on itself and to prevent well blowouts
- ❖ The drilling mud will carry the formation cuttings to the surface, and its density must be adequate enough to have the cuttings suspended inside of it during drilling pauses
- ❖ The mud provides hydraulic energy to the tools and the bit, it is what makes the drill bit rotate

The drilling mud is prepared using either bentonite and/or barite depending on what type of formation is present, along with additives, emulsifiers, and gellants to give the fluid the rheological properties required by the formation. There are two types of drilling fluids:

- Water-based muds: as its name suggests, the liquid that is more present, also called the continuous phase, is water, while oil is the dispersed phase. This type of drilling fluid is typically used for formations containing large intervals of sandstone.
- Oil-based muds: in this mud, the oil is the continuous phase, and water is the dispersed phase. The oil is usually diesel, however, kerosene and fuel oil are sometimes also used. This type of drilling mud is used mostly for formations that contain shales; because shale is a hydrophilic type of rock, meaning that it likes water, so if a water-based mud were to be used, the shales would absorb the water from the drilling fluid compromising the integrity of the well.

[44] *Id.*

Drilling operations are performed in different stages according to the drilling plan established previously, once a stage has been reached the casing is lowered, followed by cement to keep the casing in place, afterwards a sonic log can be run to check if the cementing was successful and if it meets the drilling requirements. After this is done the drilling of the next stage can proceed, and this process repeats itself until the desired depth interval is reached. During this entire process the drilling engineers must be monitoring pressures, densities, rates of penetration, the cuttings, and many other variables 24 hours a day, therefore AI aids engineers and supervisors during this constant monitoring. If the AI used by the drilling early warning system identifies a certain pattern that it deems to be risky, it immediately notifies the engineers and it is them who make the decision on how to proceed next, since there are lives and the environment at stake. It is through a constant cooperation of engineers and artificial intelligence that an early warning system works, the algorithm helps the engineers make these crucial decisions by giving them the insights they need on the situation at hand, and it is the human counterpart who will make the according choice.

Applications of AI in Early Warning Systems for Geopolitical Risks

As has been seen in chapter 3 with the many examples of the conflicts that Russia and Ukraine have had over the years, as well as that between Chile and Argentina in 2004, geopolitical conflicts can often lead to energy disruptions. In these scenarios, if the technology had been available back then, AI could have analyzed intricate market dynamics, helping energy organizations make profitable and well-informed trading decisions by processing real-time data on supply, demand, and pricing trends; nowadays, this is being done by every nation and company on the planet that deals in this branch of energy. AI is also very good at risk management, proactively evaluating the uncertainty and volatility of the market, depending on many factors and even by analyzing social media posts that for some could be unrelated to the situation, but deep down reflect the coming of a possible conflict. AI-powered algorithmic trading can complete many trades in milliseconds, and through this the energy portfolios of companies and countries are optimized, market scenarios are simulated, chores are automated, and it is constantly adjusting to shifting conditions of the market, AI can identify market opportunities and threats that human traders might miss thanks to pattern recognition skills of the model used by AI, this allows it to train itself on new patterns and trends.

In order to handle the problems of the global energy environment, policymakers in industrialized nations must adopt comprehensive energy policies at the national level in order to address geopolitical concerns. The transition of energy towards renewable energy sources is heavily influenced by geopolitical risk. Caldara and Iacoviello (2022) define geopolitical risk in the following way:

"Geopolitical risk is defined as the threat, realization, and escalation risk triggered by adverse events related to tensions between nations concerning war, terrorism, and the disruption of international relations and peace processes."[45]

Geopolitical risks in energy systems, like supply chain disruptions, resource scarcity, and climate change, are global issues that concern every country, therefore nations have to collaborate between them to have effective responses to these risks, countries can accelerate the rate at which they are developing their AI algorithms for energy systems if they put in their resources, knowledge, and expertise leading to a constant system innovation that benefits all of them. If countries work together, like the European Union does, they can create an environment where their citizens can benefit from their energy systems, which leads to a reduction of geopolitical tensions. The countries involved can establish agreements focused on AI research and development in energy systems, where they can set goals, and funding.

To better understand how geopolitical risks can affect the transition of energy, Qiang Wang, Xinhua Wang, and Rongrong Li in their 2024 article "*Geopolitical risks and energy transition: the impact of environmental regulation and green innovation"*[46] analyzed these effects in the member countries of the OECD because of two main reasons:

1. The importance of geopolitical risks and energy transition of OECD member countries in economic and environmental policies, these policies have heavy impacts on a national and international scale.
2. OECD countries have a higher geopolitical risk index than the global average.

The study focused on 20 OECD countries from 1991 to 2020, generating a dataset with 600 observations using data sources like:

- Geopolitical Risk (GPR): which was obtained from Geopolitical Risk Index of Caldara and Iacoviello[47].
- Energy Transition (ET): which was measured as the percentage of renewable energy in total energy consumption, obtained from the World Development Indicators (WDI) of the World Bank[48].
- Green Innovation (GI): it represents the share of environmental-related technologies within total technological advancements, sourced from the OECD database.[49]

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[45] Caldara D, Iacoviello M. (2022) *Measuring geopolitical risk*. American Economic Review 112(4):1194–1225. https://doi.org/10.1257/aer.20191823

[46] Wang, Q., Wang, X. and Li, R. (2024, September 27). *Geopolitical risks and energy transition: the impact of environmental regulation and green innovation.* Humanit Soc Sci Commun **11**, 1272. https://doi.org/10.1057/s41599-024-03770-3

[47] Caldara D, Iacoviello M. *Op.Cit.*

[48] World Bank Group (2024) *World Development Indicators.* https://databank.worldbank.org/source/world-development-indicators

[49] OECD (2024). *"Metrics for Green Innovation".* OECD. https://www.oecd.org/en/topics/metrics-for-green-innovation.html (accessed on 24 October 2024).

- Environmental Regulation (EPS): Environmental Policy Stringency Index sourced from the OECD database.[50]

Inflation, natural resource rents, economic globalization, and exchange rates, were used as control variables and they were collected from the WDI.

Wang and the other authors developed a linear regression model in their article to explore the impact of geopolitical risks on the transition of energy for the selected OECD countries which represents the relationship between energy transition, geopolitical risk, rate of inflation, natural resource rents, economic globalization, and the exchange rate. This model is shown below in equation 1:

$$ET = F(GPR, IFLA, NRR, EG, EXR)$$

Where:

ET, energy transition

GPR, geopolitcal risk

IFLA, rate of inflation

NRR, natural resource rents

EG, economic globalization

EXR, exchange rate

Afterwards, Wang, Wang, Li applied the natural logarithm transformation and data mining to the previous equation and they obtained the following equation, equation 2, where they showed that environmental regulations have a moderating effect on the impact of geopolitical risk on energy transition.

$$lnET_{it} = \alpha + \beta_1 lnGPR_{it} + \beta_2 lnIFLA_{it} + \beta_3 lnNRR_{it} + \beta_4 lnEG_{it} + \beta_5 lnEXR_{it} + \varphi_{it}$$

Where:

α, is the intercept term

β, are the parameter estimates of each variable

i, i = 1…, N represents the OECD countries

[50] OECD (2024). *"Environmental policy: Environmental Policy Stringency index".* OECD Environment Statistics (database). https://doi.org/10.1787/2bc0bb80-en (accessed on 24 October 2024)

t, t = 1, …, T represents time

φ, is the error term

The explained variable of their study is ET, and the core explanatory variable is GPR. In other words, they tried to figure out how much did geopolitical risk affected energy transition.

Furthermore, they also discovered that green innovation has a moderating effect on the impact of geopolitical risks through the following equation, equation number 3:

$$lnET_{it} = \alpha + \beta_1 lnGPR_{it} + \beta_2 lnEPS_{it} + \beta_3 lnGPR_{it} \times lnEPS_{it} + \beta_4 Controls_{it} + \varphi_{it}$$

Where:

EPS, is the Environmental Policy Stringency Index

Controls, refer to the control variables like inflation, natural resources rent, etc.

After Wang, Wang, and Li developed and ran their models, they obtained the following graph where the geopolitical risk index of the chosen OECD was charted, and the vertical axis represents the geopolitical risk index while the horizontal axis represents time.

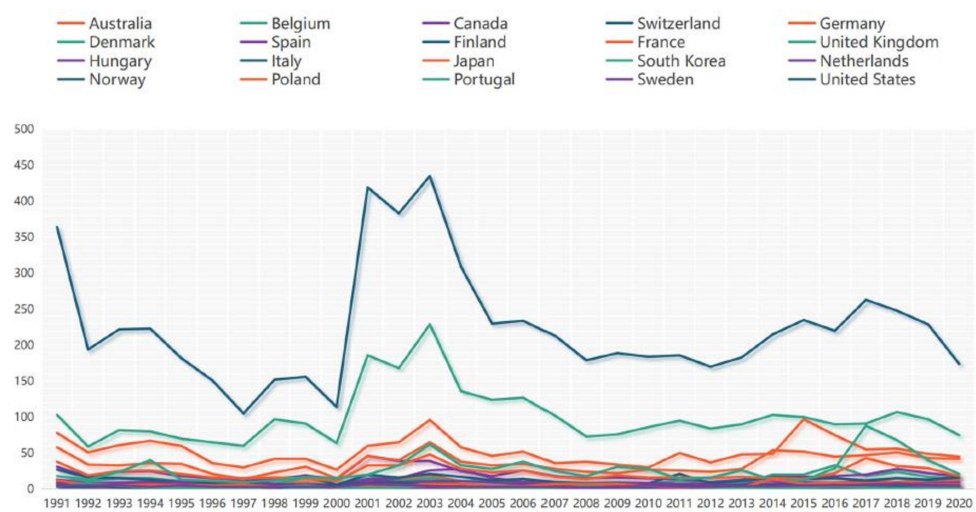

Figure 6.4: Geopolitical risks index of the OECD countries chosen for their study[51]

Because of their choice of colors to represent the countries in the graph, it is unclear which is the country with the highest geopolitical risks index since Norway, Italy, Finland, Switzerland, and the United States have the same

[51] Wang, Q., Wang, X. and Li, R. (2024, September 27). *Geopolitical risks and energy transition: the impact of environmental regulation and green innovation.* Humanit Soc Sci Commun **11**, 1272. https://doi.org/10.1057/s41599-024-03770-3

shade of blue; the same argument can be made for the country that has the second-to-highest geopolitical risks index, since Belgium, Portugal, South Korea, and the United Kingdom have the same shade of turquoise. However, it is possible to make a good guess as to which countries are the ones that have the highest geopolitical risks index; according to the analysis of the results made by the author of this thesis, the models of Wang, Wang, and Li have put the United States as the country with the highest geopolitical risks index followed by the United Kingdom, this affirmation is made by looking at the horizontal axis, which represents time, and by focusing on the trends followed during the year of 2000 – 2001. On September 9, 2011 the United States suffered the most devastating terrorist attack the world has ever seen which led to the collapse of the Twin Towers in New York City. By looking at the graph made by Wang, Wang, and Li it can be seen that the geopolitical risks index spikes for a country that is shaded in blue, and since the United States is a country that is shaded in this color, it is a fair assumption to be made that this trend line corresponds to that of the United States, meaning that the US has the highest geopolitical risks index of all member countries of the OECD. For the case of the UK, this country has been a close ally of the United States since the beginning of the twentieth century, and therefore what affects the United States is sure to affect, although to a lesser extent, the United Kingdom.

Regarding the results obtained by Wang, Wang, and Li their models showed that as geopolitical risks increase, countries tend to accelerate their push towards renewable energies to reduce their reliance on non-renewable energy sources, especially those energy sources that come from another country, as is the case with many countries in Europe and their dependance on Russia for gas. However, this does not mean that geopolitical risks index and energy transition have a linear relationship, on the contrary, they have a nonlinear relationship, in other words, as environmental policies and green innovation strengthen, the impact of geopolitical risks on energy transition is more noticeable over time. The stronger the environmental policies and technological advancements in green innovation that a country has, the faster their transition to renewable energy sources.

Lastly, the study made by Wang, Wang, and Li recommends that the policymakers in the chosen OECD countries adopt strategies that combine strict environmental regulations with investments in green innovation because this will ensure that geopolitical risks lead to lasting, positive changes in the energy sector. The OECD countries that were selected for this study are advised to improve their environmental policies to help the energy transition process, this can be done through more investments in research and development of renewable energy technologies, tax cuts for industries and households that push for cleaner energy, stricter emission controls, and regulations that support the adoption of green technologies. For more details on the models, methodology, results, discussion, and conclusions, please consult the article written by Qiang Wang, Xinhua Wang, and Rongrong Li, *Geopolitical risks and energy transition: the impact of environmental regulation and green innovation*.[52]

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[52] *Id.*

Another, and more recent, example of how geopolitical risks can impact the energy sector is given by Figueiredo, Solaiman, Al – Alawi, and Sousa in their article *The Impacts of Geopolitical Risks on the Energy Sector: Micro-Level Operative Analysis in the European Union*[53] where they focused on how the effects of geopolitical risks at a micro – level could affect the energy sector in EU countries. The main focus of this paper explains that the shift from fossil fuels to renewable energy will lead to significant geopolitical changes, this is because countries that are rich in fossil fuels usually have a lot of geopolitical influence around the world and the countries that are dependent on them will gain more energy independence by adopting renewable energy technologies. Countries that are able to adapt to these changes by securing stable, renewable energy sources will be more prepared to face geopolitical risks, while those that remain dependent on fossil fuels may face increased vulnerability to energy supply disruptions and geopolitical instability.

The study done by Figueiredo, Solaiman, Al – Alawi, and Sousa used data coming from Eurostat to perform a multiple regression model, that tried to explain how different energy components influence energy consumption at a micro level. The dependent and independent variables defined were the following:

- Dependent variable
  - Energy Consumption
- Independent variables
  - Energy Productivity: is the economic output per unit of energy consumed, representing the efficiency and benefits gained from energy use
  - Energy Intensity: it measures the inefficiency of the energy consumption of an economy relative to its economic output
  - Energy Efficiency: it represents efforts to perform economic tasks with lower energy usage, aligned with sustainable development goals
  - Energy Supply by Product: it indicates the total energy supply across all products

Their regression models were built using the Ordinary Least Squares estimation method which minimizes the sum of squared differences between observed and predicted values of energy consumption. From the four models they built, the most effective model was the one that had Energy Productivity, Energy Intensity, and Energy Efficiency, and this resulted in their model 83.7% of the variability in energy consumption and showing a strong fit with the data. The equation is shown below:

[53] Figueiredo, R.; Soliman, M.; Al-Alawi, A.N.; Sousa, M.J. (2022, November 28). *The Impacts of Geopolitical Risks on the Energy Sector: Micro-Level Operative Analysis in the European Union*. Economies 2022, 10, 299. https://doi.org/10.3390/economies10120299

$$Y = 142{,}163.49 - 2326.47\ Energy\ Productivity - 705.01\ Energy\ Intensity + 12{,}055.32\ Energy\ Efficiency$$

Since this was the model that best fit the data, this means that these variables can significantly predict energy consumption, supporting the hypothesis of the study that stated that geopolitical risks, indirectly influence these energy characteristics, and can therefore impact energy consumption at the micro level in EU states. However, as has been discussed in this thesis, linear models take data from the past to try and forecast a scenario in the future, and it is here where AI can play a significant role to improve these systems and help nations prepare themselves for any crisis that might unfold.

AI systems are constantly obtaining information from different data sources with the goal of identifying a pattern that it recognizes as a probable negative situation, these data sources can include news articles, social media posts (as has been previously mentioned), and economic indicators. In this case, AI uses Natural Language Processing (NLP) techniques, which basically gives computers the ability to understand how humans communicate with each other, how they interact with each other, and more importantly how humans use computers to talk to one another. It is through these machine learning techniques that AI can identify patterns and keywords that it recognizes as emerging geopolitical risks, like military movements or speeches during political campaigns, and this gives organizations all the tools that are necessary for them to take the appropriate decisions. Some of the applications of Natural Language Processing can be seen in the figure below:

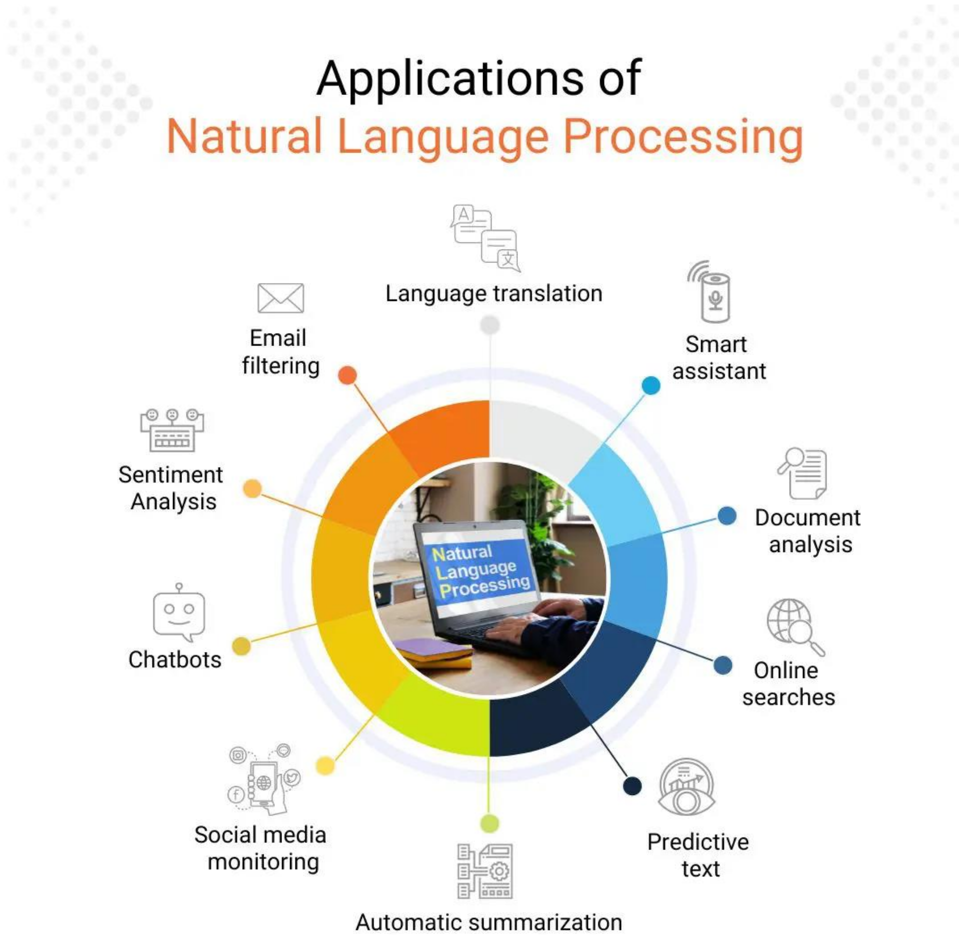

Figure 6.5: Applications of Natural Language Processing[54]

The entire process of AI analyzing data coming from many different sources, for it to later identify a pattern from which humans can then make a prospective prediction of how a situation might unfold is called predictive analytics, and it is being used more frequently to assess and manage geopolitical risks that can impact various sectors, this is because organizations must always be on the lookout for what could affect their strategies, portfolios and interests.

Large Language Models in combination with Natural Language Processing are deciphering how humans communicate with one another, but more importantly they are understanding human behavior through the way they express each themselves within different situations. The historical data that is being used to train models always has different connotations depending on when it was said. As an example of this consider the days before Russia attacked Ukraine back in February of 2022, the social media posts made by Russian citizens, especially

[54] Alam, M.F. (2022, September 8). *Applications of Natural Language Processing.* Datasciencedojo. https://datasciencedojo.com/blog/natural-language-processing-applications/

young people, the girlfriends, wives and mothers of already enlisted soldiers where they were uploading images that could be considered heart-warming because they were saying goodbye to their boyfriends, husbands and sons for an unknown-at-the-time situation; the AI used by the EWS of the United States identified a pattern that lead to the American government issuing a warning for its citizens to get out of Ukraine as soon as possible. The Large Language Models and Natural Language Processing techniques were exposed to how humans behave in these kinds of situations. However, this event where young men say their goodbyes to their friends and family in the United States, is not identified as a negative pattern by a Russian EWS because of the context and the data that their systems used to train with. The effectiveness of an EWS that employs AI is related to the time and the space of the pattern, and it is through cooperation with humans that an EWS that uses AI can be considered as effective.

Universities, research institutions, and private organizations can help governments develop frameworks, where they can exchange energy system while also adhering to strict privacy laws and regulations, especially whilst dealing with sensitive data that could impact national security or economic stability; nations have to be transparent without putting themselves at geopolitical risk, thus they have to establish committees where they can agree as to what kind of information they can share and how much of it. Data sharing standards and ethical guidelines concerning data privacy, security, and cooperation between countries must be established for the use of AI in their energy systems. These guidelines will regulate how data is collected, processed, and used in AI applications for energy systems, to ensure energy security and support the transition towards a cleaner, more sustainable energy system.

Conclusions

The security of the gas supply of a nation is as crucial as the resource itself, there is no point in having a large amount of gas stored if the infrastructures is inadequate and it is impossible for the citizens of a nation to have any use of it. Even though the amount of natural gas produced by Italy is not enough to meet the demand of its citizens, and considering the fact that before the conflict between Russia and Ukraine, Russia was the main supplier of gas to Italy, the energy policy of the Italian government enabled the country to quickly adapt gas suppliers and now Italy has shown that it has the capacity to guarantee energy security for its citizens. As is the case with the entire European Union, by switching suppliers and pushing even more towards the transition of energy.

Geopolitical risks often lead to energy crises, although these crises can also be caused by natural disasters, and the ability of governments, organizations, and communities to quickly mitigate the situation before it grows into an even larger issue is crucial. Therefore, early warning systems are an essential tool to give time to stakeholders to evaluate their options to best tackle the situation that is currently unfolding. Timely preparedness can be the difference between a well-managed problem that was resolved efficiently, and a tragedy that could lead to an even larger issue.

Early warning systems are an alert that notifies organizations that there are certain current indices of a negative situation that is brewing and that there is still time to take precautions to completely avoid it or de-escalate it. These systems are based on the identification of patterns, and although they are built upon traditional regression models, artificial intelligence is now taking the spotlight of how they work. Artificial intelligence that uses deep learning models are the current best fit for early warning systems since they can process large amounts of information coming from different sources in an incredibly short time. This constant processing of information gives the model the ability to search for patterns that it might recognize as indices to emit the early warning by comparing the information it has to the one it was trained with. The true way early warning systems of nations work is impossible to know as this information is top-secret since it is a matter of national security and exposing the inner workings of it would be devastating because it gives a view as to how to bring it down or have set it off.

In order to have a more energy independent country, nations must also push towards the transition of energy. As was seen in some of the models developed by other authors but studied in this thesis, when geopolitical risks increase so does the transition to renewable energies. This happens because depending on another nation for something as crucial as natural gas can affect a country greatly if for some reason the supply came to a halt and the country does not have the capacity nor preparedness to adapt to these changes. Therefore, the only option is to accelerate the transition of energy, also contributing in the fight against climate change and meeting these goals.

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