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Blockchain-enabled emission management system in the natural gas supply chain.

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Blockchain-enabled emission management system in the natural gas supply chain.

Nikolas Michail Kanellopoulos

Abstract

The objective of this research is the examination of the utilization of Blockchain technology in the natural gas supply chain, with a key emphasis on the efficient monitoring of emissions.

Blockchain technology, which is the foundation of cryptocurrencies such as Bitcoin, provides an integrated platform of development for applications that require transparency, efficiency, and traceability.

The ambitious plan of achieving net-zero emissions by 2050 highlights the necessity of developing precise and transparent reporting solutions. Such solutions would equip regulators and businesses with the essential tools to identify production bottlenecks that cause excessive emissions, facilitating their resolution and stimulating the refinement of current regulations.

This research focuses on the design and the development of a blockchain-enabled emission management system in the natural gas supply chain system. This study includes:

- An overview of the fundamental processes within the life cycle of natural gas.
- An analysis of the basic principles of blockchain technology.
- The creation of a simplified mapping system to trace the source of emissions within the natural gas supply chain, based on data obtained by EPA reports.
- The implementation of this mapping system into a pseudo-blockchain application that adheres to the principles of blockchain technology.

This thesis aims at validating the feasibility of such an application and establishing the foundation for future expansion. This includes the further development of the mapping system and the creation of an operational decentralized application capable of real-time data collection.

Blockchain-enabled emission management system in the natural gas supply chain.

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Σύνοψη

Ο στόχος αυτής της διπλωματικής είναι η μελέτη της εφικτότητας εφαρμογής της τεχνολογίας Blockchain στην εφοδιαστική αλυσίδα του φυσικού αερίου, με στόχο την αποτελεσματική καταγραφή ρύπων.

Το Blockchain, που αποτελεί την τεχνολογία πίσω από τα κρυπτονομίσματα όπως το Bitcoin, προσφέρει την δυνατότητα ανάπτυξης εφαρμογών που χαρακτηρίζονται από διαφάνεια και ιχνηλασιμότητα.

Παράλληλα, ο φιλόδοξος στόχος για την επίτευξη μηδενικών εκπομπών αερίων του θερμοκηπίου μέχρι το 2050, τονίζει την αναγκαιότητα ανάπτυξης εφαρμογών που εξασφαλίζουν αξιόπιστες και ακριβείς μετρήσεις ρύπων. Μια τέτοια εφαρμογή παρέχει τα κατάλληλα εφόδια στην βιομηχανία και τους ρυθμιστικούς φορείς ώστε να εντοπίσουν τις αδυναμίες στην βιομηχανία που οδηγούν στην έκλυση υψηλών ρύπων. Με αυτό τον τρόπο, θα διευκολυνθεί η εύρεση λύσεων σε περιβαλλοντικά ζητήματα και θα εξελιχθεί το υπάρχον ρυθμιστικό πλαίσιο.

Η μελέτη της παρούσας διπλωματικής επικεντρώνεται στον σχεδιασμό και ανάπτυξη ενός συστήματος καταγραφής ρύπων της εφοδιαστικής αλυσίδας του φυσικού αερίου, βασιζόμενο στην τεχνολογία Blockchain. Η μελέτη αποτελείται από:

- Περιγραφή των κυρίων διεργασιών διύλισης του φυσικού αερίου.
- Ανάλυση των βασικών χαρακτηριστικών της τεχνολογίας Blockchain.
- Χαρτογράφηση των διαφόρων πηγών ρύπων στην εφοδιαστική αλυσίδα του φυσικού αερίου, η οποία βασίζεται σε δεδομένα από την EPA.
- Ανάπτυξη pseudo-blockchain εφαρμογής που βασίζεται στην χαρτογράφηση.

Η παρούσα διπλωματική στοχεύει στην επικύρωση της σκοπιμότητας μιας τέτοιας εφαρμογής και στην δημιουργία των θεμελίων για μελλοντική επέκταση. Η επέκταση θα περιλαμβάνει την περαιτέρω εξέλιξη της παρούσας χαρτογράφησης και την δημιουργία μιας λειτουργικής αποκεντρωμένης εφαρμογής ικανής να συλλέγει δεδομένα σε πραγματικό χρόνο.

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Introduction

The need to reduce greenhouse gas (GHG) emissions is imminent and urgent. The world is already affected by climate change, with extreme weather conditions such as drought, heat waves, heavy rain, floods, and landslides becoming more frequent. The world is facing a critical juncture in its history where immediate action is required to avoid catastrophic consequences.

Under the Paris Agreement, the goal is to limit global warming to 1.5 degrees C°, a threshold the Intergovernmental Panel for Climate Change (IPCC) suggests is safe. Therefore, in December 2019 when the European Commission presented the European Green Deal [1], the ambitious goal of achieving **“net zero”** by 2050 was adopted.

Many solutions aimed at mitigating climate change have been proposed [2]:

- Retire coal plants.
- Adopt clean energy.
- Shift to electric vehicles.
- Decarbonize shipping and aviation.
- Decarbonize cement, steel, and plastics.

Obtaining high quality emissions data has become crucial for policymakers in shaping climate change policies. The energy sector, being one of the main contributors in global GHG emissions, is under pressure to disclose the carbon dioxide emissions associated with their product. In **Natural Gas Systems**, the main subject of this thesis, several countries require the reporting of greenhouse gas emissions. For instance:

- **United States**: The U.S. Environmental Protection Agency (**EPA**) has established the **Mandatory Greenhouse Gas Reporting Rule** (40 CFR Part 98) requiring the reporting of GHG emissions from natural gas systems. Companies involved in these activities must report their emissions annually.
- **Canada**: The federal government and some provinces have implemented GHG reporting regulations, adopting the federal "**Large Final Emitters Program**".
- **European Union**: The European Union has established the **EU ETS (European Union Emissions Trading System)**, which includes mandatory reporting of GHG emissions from various sectors, including energy production and distribution.

In addition to meeting regulatory requirements, there is a growing demand for manufacturers to disclose their carbon dioxide emissions to their stakeholders, a practice also known as carbon transparency.

Studies have shown a positive correlation between environmental disclosure and corporate financial performance [3]. For instance, knowing that their carbon emissions will be made public, manufacturers are more likely to implement a carbon management strategy that reduces energy wastage, that can eventually lead to savings in energy expenses.

A powerful tool that can ensure transparency in the reporting of GHG emissions is **Blockchain technology.** It helps companies to improve the accountability and traceability of their GHG Emissions by providing accurate, reliable, and readily available data on carbon emissions. In general, some of the benefits deriving from the use of blockchain technology include [4, 5]:

- **Traceability:** Effective mapping and visualization of emissions records in each step of the supply chain.
- **Transparency:** The increased traceability of data enhances transparency, and therefore trust among the parties of the network is cultivated.
- **Speed**: Improved calculation, tracking, and reporting of carbon footprint reduction, using smart contracts.
- **Immutability:** The blockchain is fraud-resistant since it is a distributed ledger consisting of multiple copies. Tampering with a specific transaction is almost impossible since one must alter all the copies simultaneously.
- **Data Accuracy**: The blockchain provides instant authentication and real-time data verification, ensuring data accuracy.
- **Consensus:** The blockchain requires that all involved parties come to a mutual agreement on the actions that need to be taken.

This thesis aims at providing:

- A detailed examination of the natural gas supply chain.
- A presentation of the key features of blockchain technology
- An outline of the approach for the development of a blockchain-enabled emission management system tailored to the natural gas supply chain.

Chapter 1 : Theoretical Background

1.1 Natural Gas Supply Chain

The natural gas supply chain is a complex network of processes and infrastructure dedicated to the extraction, refining and distribution of natural gas. This supply chain consists of several stages such as:

- **Exploration:** This is the initial phase of the natural gas system development and consists of activities such as drilling and testing. Companies examine the prospective natural gas reservoirs and evaluate the wells to determine their production capacity. If the gas well proves to be productive, then necessary equipment is installed that facilitates the extraction of gas.
- **Production:** This phase concerns the extraction of raw gas from underground formations through wells.
- **Processing:** After extraction, natural gas often undergoes processing to remove impurities and separate valuable components like methane from other gases and liquids. This processed gas is known as pipeline-quality natural gas.
- **Transmission:** Natural gas is transported from the processing facilities to distribution points through high-pressure pipelines. At several points along the way, gas passes through compressor stations, that help it maintain the appropriate pressure.
- **Storage:** Natural gas is often stored in underground reservoirs during periods of low demand and withdrawn when demand is high. Storage helps ensure a consistent and reliable supply of gas throughout the year.
- **Distribution:** Natural gas is distributed to homes, businesses, and industrial facilities through a network of lower-pressure pipelines.

Natural gas is considered to be a relatively clean burning fossil fuel, however, during each stage of the natural gas lifecycle described above, emissions are produced. These emissions are mainly:

Methane CH_4: Natural gas is a naturally occurring gas mixture, consisting mainly of methane (typically 94.7%) and other components at lower concentrations such as Ethane, Propane, Nitrogen and CO_2 (typically 4.2%, 0.2%, 0.5%, 0.3% respectively) [6].

Methane is the second most abundant greenhouse gas, after carbon dioxide. Even though it breaks down more quickly than CO_2, CH_4 traps 80 times more heat, making it a major contributor to climate change [7].

Methane is released to the atmosphere through natural gas leaks from pipelines. In 2020, the U.S EPA (Environmental Protection Agency) suggested that CH_4 emissions from natural gas and petroleum systems and from abandoned oil and natural gas wells were the source of about 33% of total U.S. methane emissions and about 4% of total U.S. greenhouse gas emissions [8].

Carbon Dioxide CO_2: As mentioned above, carbon dioxide is the most abundant greenhouse gas. As natural gas's composition has a low CO_2 concentration, most CO_2 emissions are associated with the energy and fuel consumption required for drilling, extraction, and production activities. This includes the use of diesel engines, generators, and other equipment. Moreover, CO_2 emissions are also produced when natural gas is burned for energy or heat. However, natural gas is considered a lower-emission fossil fuel compared to coal and oil.

Nitrous Oxide N_2O: Nitrous oxide emissions from the natural gas supply chain are generally less significant than methane and CO2 emissions. These emissions can occur during the combustion of natural gas or as a byproduct of certain chemical reactions in industrial processes.

In general, the exact emissions levels can vary depending on factors such as the source of natural gas and the efficiency of equipment and processes.

For instance, the CH_4 content in raw gas by US region (gas wells with hydraulic fracturing) from year 2006 – 2021 [8] is presented in figure:

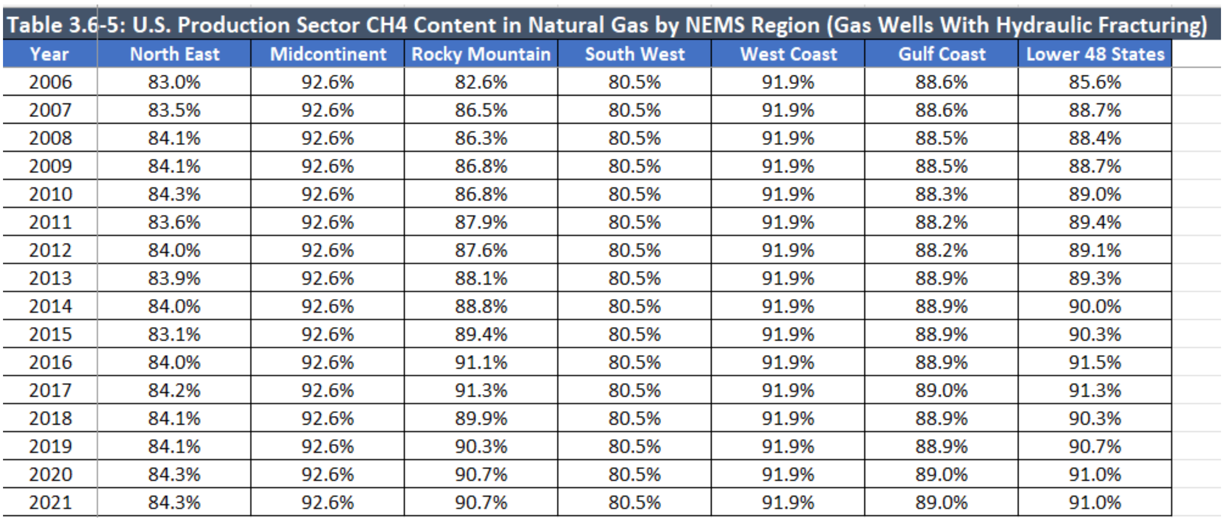


Table 3.6-5: U.S. Production Sector CH4 Content in Natural Gas by NEMS Region (Gas Wells With Hydraulic Fracturing)

Year	North East	Midcontinent	Rocky Mountain	South West	West Coast	Gulf Coast	Lower 48 States
2006	83.0%	92.6%	82.6%	80.5%	91.9%	88.6%	85.6%
2007	83.5%	92.6%	86.5%	80.5%	91.9%	88.6%	88.7%
2008	84.1%	92.6%	86.3%	80.5%	91.9%	88.5%	88.4%
2009	84.1%	92.6%	86.8%	80.5%	91.9%	88.5%	88.7%
2010	84.3%	92.6%	86.8%	80.5%	91.9%	88.3%	89.0%
2011	83.6%	92.6%	87.9%	80.5%	91.9%	88.2%	89.4%
2012	84.0%	92.6%	87.6%	80.5%	91.9%	88.2%	89.1%
2013	83.9%	92.6%	88.1%	80.5%	91.9%	88.9%	89.3%
2014	84.0%	92.6%	88.8%	80.5%	91.9%	88.9%	90.0%
2015	83.1%	92.6%	89.4%	80.5%	91.9%	88.9%	90.3%
2016	84.0%	92.6%	91.1%	80.5%	91.9%	88.9%	91.5%
2017	84.2%	92.6%	91.3%	80.5%	91.9%	89.0%	91.3%
2018	84.1%	92.6%	89.9%	80.5%	91.9%	88.9%	90.3%
2019	84.1%	92.6%	90.3%	80.5%	91.9%	88.9%	90.7%
2020	84.3%	92.6%	90.7%	80.5%	91.9%	89.0%	91.0%
2021	84.3%	92.6%	90.7%	80.5%	91.9%	89.0%	91.0%

Figure 1-1: CH_4 content in natural gas by US region

In the upcoming sections, the processes that contribute to emissions in the natural gas supply chain will be examined. This analysis will provide a thorough investigation of each stage of the supply chain, identifying the specific processes and activities that release greenhouse gases into the atmosphere.

The objective is to develop a detailed mapping of the natural gas supply chain. This mapping will serve as the foundational framework upon which a blockchain-based emissions management system will be built.

1.1.1 Exploration and Well Construction

The process of extracting natural gas requires the construction of wells, steady-state operations, and periodic maintenance tasks.

1.1.1.1 Well Construction and Installation

The Well Construction begins by drilling. Depending on the technical specifications of each well, different drilling techniques may be used. For instance, horizontal drilling is used for unconventional natural gas reserves where hydrocarbons are dispersed throughout a matrix of shale or coal [9].

The second step in natural gas well construction involves the installation of a well casing, that aims at reinforcing the wellbore and preventing contamination in the surrounding geological formations [9].

The casing used for this purpose is typically made of carbon steel and is secured using concrete. The overall length of a natural gas well can vary depending on the specific natural gas extraction requirements.

The number of total materials needed for constructing a wellbore, can be calculated by multiplying the total well length by the linear weight of the carbon steel and concrete components.

Well Construction and Installation releases CH_4 and CO_2 emissions. These can be determined by measuring the methane leaks and calculating the total power of the machinery used. For instance:

A high-speed drilling rig (17.8 meters/hour) completes a 7,000-foot well in about 10 days. Typical diesel engines used (700 hp, 7,000 Btu/hp-hr) emit methane during drilling based on engine heat rate (7,000 Btu/hp-hr), emission factors, and drilling time (in hours).

It is worth noting that this is a one-off type of emission since a well is only constructed once.

1.1.1.2 Well Completion

Well completion is the final step in preparing a drilled well for production. This process focuses on getting the bottom of the well to the necessary standards.

It includes inserting the production tubing and the tools needed inside the well, as well as creating openings in the well's walls (perforating) and sometimes using stimulation techniques to enhance production as necessary. In essence, it's about getting the well ready to start producing oil or gas efficiently.

The completion of conventional and unconventional wells mainly releases methane emissions through venting and flaring. These emissions can be approximated by emissions factors calculated by the EPA [9]. For instance:

- Conventional wells produce 37 Mcf/completion.
- Tight gas wells produce 3,600 Mcf/completion.
- Shale gas wells produce 9,000 Mcf/completion.
- Coal bed methane wells produce 50 Mcf/completion.

1.1.2 Production

This phase involves the extraction of raw gas from underground formations using the wells constructed in exploration.

1.1.2.1 Well Workovers

Well workovers are part of maintenance and are necessary for cleaning any kind of oil and gas wells. They refer to interventions that involve invasive techniques such as wireline, coiled tubing, or snubbing [10].

This costly process involves the removal and replacement of well completions to repair existing production wells, with the goal of restoring, extending, or improving hydrocarbon production.

Well workovers produce episodic emissions, which are not part of daily well operations. These emissions arise from the occasional maintenance of a well.

According to reference [9], Well Workovers usually release big amounts of methane. For instance, a conventional well produces approximately 2.454 Mcf of methane per workover.

The average conventional well has 0.037 workovers per well year.

The average unconventional well has 0.01 workovers per well year.

1.1.2.2 Liquid Unloading

Liquid unloading refers to the release of natural gas that happens when water and other condensates are extracted from a well. These liquids can obstruct the flow of natural gas from the well, so producers must periodically eliminate them from the wellbore.

Liquid unloading is a necessary procedure for conventional gas wells, while it is generally assumed that unconventional or associated gas wells typically do not require liquid unloading as a standard practice [9].

Liquid Unloading also produces episodic emissions, that however represent a significant emission from the occasional maintenance of the well.

According to reference [9], liquid unloading releases 3.6 Mcf of natural gas per episode.

The average conventional well has 31 liquid unloading episodes per year.

1.1.2.3 Well Pad Equipment

In general, the Well Pad is a specific area where one or more wells are drilled and operated. Well pad equipment refers to the various machinery, infrastructure, and components located at these well pads to facilitate the extraction of natural gas. The most emission-producing well head machinery is:

- Heaters
- Separators
- Dehydrators
- Compressors
- Meters/Piping

1.1.2.3.1 Heaters

Heater's main role is to maintain the correct viscosity of petrochemical materials when processing in extreme temperature conditions [11]. Moreover, they assist in preventing freezing of wellhead equipment when operated under cold weather conditions.

The heaters release methane and primarily carbon dioxide. These emissions occur because of the combustion process required to generate heat. They usually utilize the extracted natural gas for combustion. Several variables influencing the carbon dioxide emissions generated by heaters include:

- Fuel Type
- Combustion Efficiency
- The operation of emission control technologies such as catalytic converters and exhaust gas recirculation system.

1.1.2.3.2 Separators

An oil and gas separator, located near the wellhead, is a pressurized container designed to divide a mixture from the well into its gaseous and liquid parts [12].

Moreover, separators are often used in the gas industry to separate various components and impurities from raw natural gas.

Natural gas produced from oil and gas wells typically contains a mixture of hydrocarbons, water, liquid condensates, and impurities such as sand, mud, and other solids.

To make natural gas suitable for transportation and further processing, it needs to undergo a separation process to remove these unwanted components.

Leaks or venting of unburned natural gas, as a result of the separator's operation, can contribute to GHG emissions, including CO_2 and CH_4.

1.1.2.3.3 Dehydrators

Dehydrators are used for eliminating water from natural gas, making it suitable for pipeline transportation and enhancing its heating value.

A usual dehydration unit consists of an absorber vessel that contains a glycol-based solution which comes into contact with raw gas. A common dehydration configuration is presented in figure 1-2 [13] :

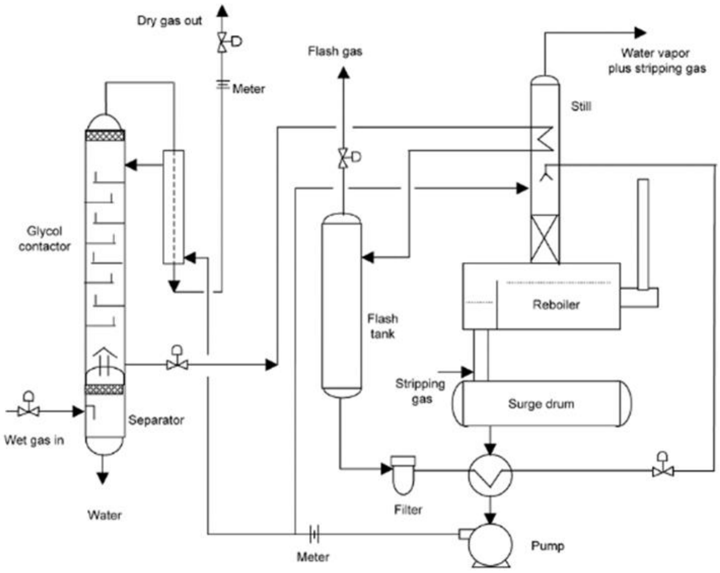


Figure 1-2: Configuration of a dehydration unit

The GHG emissions released by a dehydrator unit are mainly CH_4 and CO_2 from leaks and machinery operation. As the configuration of figure 1-2 suggests, the main system that consumes fuel (most commonly the extracted natural gas) is the reboiler.

According to reference [9], the fuel consumption of the reboiler is 1.48E-04 kg of natural gas per kg of dehydrated natural gas.

1.1.2.3.4 Compressors

The primary role of compressors is elevating natural gas pressure to a level suitable for pipeline transportation or industrial processing. Natural gas, being a low-density fuel, cannot be easily transported over long distances without compressions [14].

Compressor stations can be found in multiple stages across the natural gas supply chain, such as extraction, processing, and distribution.

Emissions from compressors include:

- CH_4 emissions from leaks and venting.
- CO_2 and NOx emissions from engine combustion.

Figures 1.3,1.4, developed by the GHG institute [34], present an interesting approach on GHG emissions calculation from compressors:

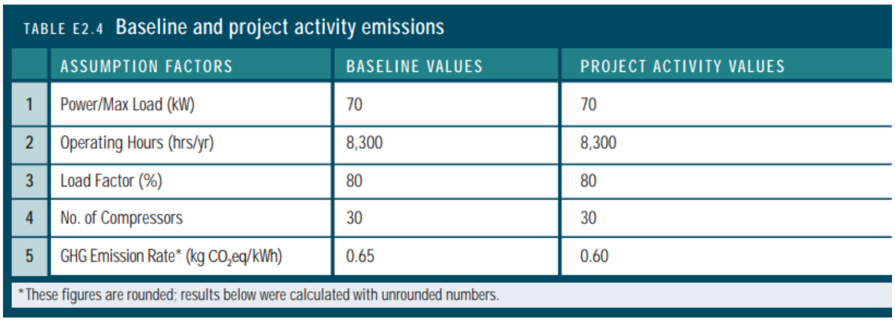
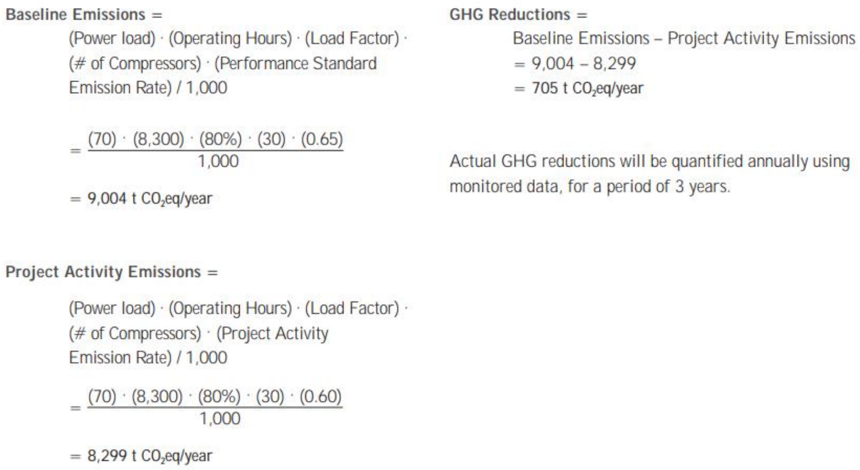


TABLE E2.4 Baseline and project activity emissions

	ASSUMPTION FACTORS	BASELINE VALUES	PROJECT ACTIVITY VALUES
1	Power/Max Load (kW)	70	70
2	Operating Hours (hrs/yr)	8,300	8,300
3	Load Factor (%)	80	80
4	No. of Compressors	30	30
5	GHG Emission Rate* (kg CO_2eq/kWh)	0.65	0.60

*These figures are rounded; results below were calculated with unrounded numbers.

Figure 1-3: Compressor emissions parameters



Baseline Emissions =

(Power load) · (Operating Hours) · (Load Factor) · (# of Compressors) · (Performance Standard Emission Rate) / 1,000

$$= \frac{(70) \cdot (8{,}300) \cdot (80\%) \cdot (30) \cdot (0.65)}{1{,}000}$$

= 9,004 t CO_2eq/year

GHG Reductions =

Baseline Emissions – Project Activity Emissions

= 9,004 – 8,299

= 705 t CO_2eq/year

Actual GHG reductions will be quantified annually using monitored data, for a period of 3 years.

Project Activity Emissions =

(Power load) · (Operating Hours) · (Load Factor) · (# of Compressors) · (Project Activity Emission Rate) / 1,000

$$= \frac{(70) \cdot (8{,}300) \cdot (80\%) \cdot (30) \cdot (0.60)}{1{,}000}$$

= 8,299 t CO_2eq/year

Figure 1-4: Compressor emissions calculation

1.1.2.3.5 Meters/Piping

Meters/Piping refers to the infrastructure and components used in the transportation and measurement of natural gas.

Meters/Piping can be found in multiple stages across the natural gas supply chain, most commonly in extraction, transmission, and distribution.

The most common type of emissions from these components are fugitive methane emissions, meaning the unintentional release of methane in the atmosphere.

These fugitive emissions can occur due to leaks, corrosion, or improper maintenance in the piping and metering infrastructure.

1.1.2.4 Pneumatic Controllers

Pneumatic controllers are process control automation devices which are used extensively to manage valves responsible for regulating parameters like liquid level and pressure. They are usually powered by natural gas but can also be energized by compressed air.

There are four different types of pneumatic controllers categorized by how they handle the release of natural gas into the atmosphere [15]:

- **Continuous Bleed Controllers:** When the valve is stationary these controllers continuously vent gas to the atmosphere at a steady rate, and when the valve spring pushes gas out of the actuator, they also vent accumulated gas from the actuator.
- **Intermittent bleed controllers:** These controllers only release gas to the atmosphere when the valve position is moved from open to closed and back again.
- **High Bleed Controllers:** These controllers continuously and consistently release a significant amount of gas into the atmosphere as part of their normal functioning.
- **Low Bleed Controllers:** These controllers are designed to minimize or significantly reduce the continuous release of gas into the atmosphere during normal operation.

Pneumatic controllers are one of the largest sources of vented methane emissions from the natural gas industry.

1.1.3 Processing

Natural gas processing is a series of operations and techniques used to refine raw natural gas extracted from underground reservoirs into a cleaner, safer, and more marketable product.

The processing requirements of natural gas vary depending on its chemical composition. For instance, figure 1.1 demonstrates that methane concentration changes based on well location.

Considering this, a generalized flow diagram of natural gas's processing is introduced by Penn State University [16] in figure 1.5:

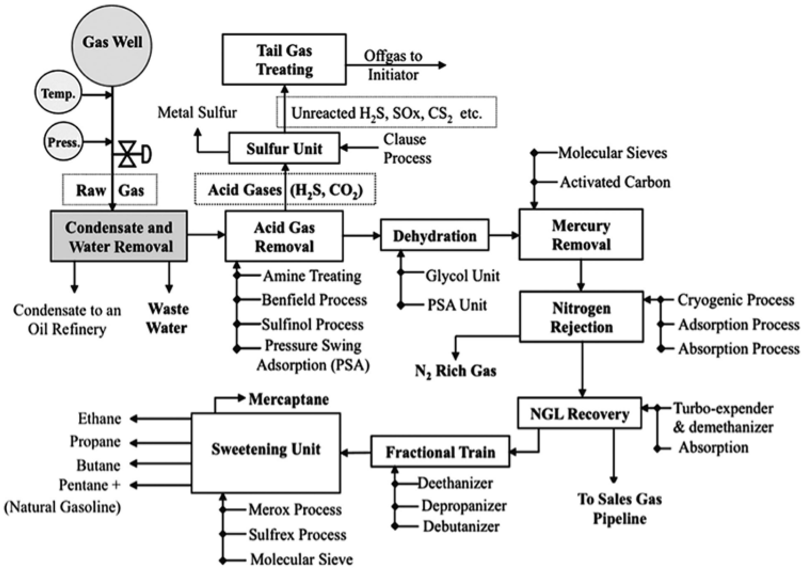


Figure 1-5: A generalized natural gas processing flow diagram by Penn State University.

1.1.3.1 Condensate and water removal

In order to process and transport natural gas, it must be first separated from the oil in which it is dissolved. This separation usually occurs at or near the wellhead.

Due to differences on the composition and processing requirements of raw natural gas depending on its source, the specific separation process and equipment used may vary.

For instance, it is quite common that natural gas becomes dissolved in underground oil primarily because of the high pressure within the geological formation. When this mixture of natural gas and oil is brought to the surface, it can naturally separate due to the decrease in pressure, similar to how opening a soda can releases the dissolved carbon dioxide. In such case, the separation is rather simple, with each hydrocarbon sent for further processing.

The simplest form of separator used for this purpose is referred to as a conventional separator, which consists of a basic closed tank. Here, gravity plays a pivotal role in the separation process, with heavier liquids like oil settling at the bottom, while lighter gases like natural gas rise to the top [17].

In complex cases where separating oil and natural gas isn’t that straightforward, specialized equipment like the Low-Temperature Separator (LTX) may be needed. This separator is commonly used for high-pressure gas wells with light crude oil or condensate.

LTX separators use pressure differences to cool and separate the wet natural gas from the oil and condensate. The process involves cooling the gas, removing liquids, and lowering the temperature through pressure changes to extract oil and water from the gas stream. This same principle can be reversed to extract gas from a liquid oil stream.

1.1.3.2 Acid Gas Removal (AGR)

Acid gas removal is a crucial process in natural gas processing that focuses on eliminating acidic components, such as hydrogen sulphide (H_2S) and carbon dioxide (CO_2), from the raw natural gas stream.

Natural gas is generally considered sour if hydrogen sulphide is present in amounts greater than 5.7 milligrams per normal cubic meters (mg/Nm^3) [18]. In this case, the gas is usually sweetened by absorption of the H_2S in an amine solution.

The emissions released during the AGR process are:

- **SO_2**: When acid waste gas from the amine process is flared or incinerated SO_2 is produced.
- **CH_4:** According to reference [9], AGR releases 0.000971 kg of methane per kg of natural gas treated.
- **CO_2**: According to reference [9], 0.013 kg of naturally occurring CO_2 is vented per kg of processed natural gas.

1.1.3.3 Dehydration – Moisture Removal

The processes employed in Dehydration and the emissions released by them are thoroughly presented in section 1.1.2.3.3.

1.1.3.4 Mercury Removal

Mercury Removal, as the name suggests, is the process of removing mercury from natural gas. Mercury can be present in natural gas as a trace contaminant and needs to be reduced to very low levels to meet environmental standards and prevent contamination and corrosion in pipelines and equipment.

According to reference [19], mercury removal can be achieved by either non-regenerative or regenerative absorption:

- Non-regenerative absorption:
    - It is usually performed using carbon impregnated sulphide beds.
    - It cannot be reused.
    - The emissions released from this method are primarily related to the disposal of the mercury-laden adsorbent material.
    - When the saturated material is removed from the Mercury Removal Unit (MRU), it becomes a waste stream that requires appropriate disposal methods to prevent environmental contamination.
    - If the waste material is incinerated or undergoes any other process that releases mercury into the air, it can contribute to mercury emissions.
- Regenerative absorption:
    - It is usually performed using molecular sieved material.
    - It can be reused.
    - It is considered that no (or minimal) mercury emissions occur.

1.1.3.5 Nitrogen Rejection

Raw natural gas frequently contains inert gas nitrogen. Nitrogen lowers the heating value of natural gas and increases transport volumes, leading to increased costs due to the larger downstream equipment such as compressors and pipelines [20].

Depending on natural gas's means of transport nitrogen content should be under a specific limit. For example, in pipeline transportation nitrogen content should be below 3-4% and in liquified natural gas (LNG) storage below 1%. There are many different methods used for nitrogen rejection such as [21]:

- Cryogenic Distillation (By far the most popular method).
- Membranes
- Solvent Absorption
- Molecular Gate System

1.1.3.6 Natural Gas Liquids Recovery (NGL Recovery)

NGL recovery serves the purpose of separating and recovering valuable hydrocarbon liquids such as ethane, propane, and butane from natural gas sources. These hydrocarbon liquids have commercial value and find applications as raw materials in the petrochemical industry, as energy sources for heating and cooking, and as additives for gasoline production. NGL recovery also helps to meet customer specifications and regulatory requirements for natural gas quality [22].

The are many different methods of achieving NGL recovery:

- Lean Oil Process (most common)
- Joule – Thomson Process
- Refrigeration Process
- Turbo – Expander Process

Depending on the method employed, the recovered liquids concentration might vary. For instance, the Lean Oil Absorption Process can typically recover about 40% of the ethane, 90% of the propane, and 95% of the pentane and heavier hydrocarbons [23].

In general, the selection of an NGL recovery process depends on the gas compositions, the gas heating content targets, and the opportunities for exporting the LPG or ethane product.

1.1.4 Transportation

In general, natural gas transportation refers to the moving of natural gas from production facilities to end-users or storage facilities. There are several methods involved in the transportation of natural gas:

- **Pipelines:** It is the most used method. Pipelines transfer natural gas in high compression over long distances. Depending on their usage, pipelines are divided in two categories:
    - **Gathering Pipelines**: These pipelines collect natural gas from individual wells and transport it to processing plants or transmission pipelines.
    - **Transmission Pipelines:** Transmission pipelines transport natural gas across long distances, often crossing state or national borders. They operate at high pressures to efficiently move large volumes of gas.
- **Liquified Natural Gas (LNG)**: When natural gas is cooled to extremely low temperatures (-161.5^{o}C) at atmospheric pressure, it condenses into liquid [24]. This liquid form is easier to transport over long distances, especially for international shipments. Specialized LNG tankers are usually used to transport LNG to receiving terminals where it is converted to its gaseous form before distribution.
- **Compressed Natural Gas (CNG)**: CNG is another method for transporting natural gas, mainly used for short to medium distances. Natural gas is compressed and stored in high-pressure cylinders or tanks on vehicles for use as a transportation fuel, such as in buses and trucks.

This thesis focuses on the transportation through pipelines. In this case, the emissions that mostly occur derive from:

- **Pipeline Leaks:** CH_4 is released into the atmosphere through leakages from the pipelines.
- **Compressor Stations:** As mentioned in section 1.1.2.3.4, compressor stations are placed in several points along the transportation network in order to maintain the appropriate natural gas pressure. The emissions are related to leaks of CH_4 and the operation of machinery (CO_2).
- **Pneumatic Controllers:** Pneumatic devices that control natural gas flow are also placed in several points along the transportation network. The emissions that usually occur in this case are related to the venting of CH_4, as section 1.1.2.4 suggests.

1.1.5 Storage

Even though there are large fluctuations in demand for natural depending on the season, production and pipeline imports are relatively constant in the short term. Therefore, it is of high importance to store natural gas in periods of low demand to ensure that enough natural gas is available during periods of high demand.

There are different types of storage facilities for natural gas such as [25]:

- **Depleted natural gas fields**: Former natural gas or oil fields that have been repurposed for storage.
- **Salt caverns**: Salt caverns are created by dissolving underground salt deposits, leaving behind empty caverns.
- **Aquifers**: Natural gas is injected into underground aquifers, which are geological formations that can hold gas without it migrating.
- **LNG Storage**: LNG storage tanks store natural gas in a liquefied form at extremely low temperatures.
- **Aboveground Storage Tanks**: Aboveground storage tanks are often used for short-term or intermediate storage, typically at distribution centers, industrial facilities, or power plants. This type of tanks usually include:
    - **Large tanks with VRU (Vapor Recovery Unit):** These tanks are equipped with vapor recovery units (VRU). These units are used to prevent emissions from light hydrocarbon vapors like methane, volatile organic compounds (VOC) and hazardous air pollutants (HAP) that when dissolved in crude oil or condensate vaporize in the space between the liquid and the fixed roof of the tank [26]**.**
    - **Large tanks without control:** These tanks do not have specific emissions control systems installed.
    - **Large tanks with flares:** These tanks have flaring systems designed to safely burn off excess gases to prevent the release of hazardous substances in the atmosphere.

  - **Small tanks with flares:** Like large tanks with flares, these tanks also burn off excess gases.
  - **Small tanks without flares:** These tanks do not have a specific system for safely burning off excess gases or emissions.

1.1.6 Distribution

Natural gas distribution refers to the process of delivering natural gas from its source, which could be transmission pipelines or storage facilities, to individual consumers, businesses, and industries. There are several components involved in natural gas distribution such as:

1. **Distribution Networks**: Distribution networks consist of pipelines, typically made of steel or plastic, that transport natural gas from transmission pipelines or storage facilities to various locations.
2. **City Gate Stations**: City gate stations are entry points where natural gas is transferred from higher-pressure transmission pipelines to lower-pressure distribution pipelines. At these stations, gas pressure is reduced to a level suitable for local distribution [27].
3. **Regulator Stations**: Regulator stations are installed at various points along the network and ensure that the appropriate natural gas pressure is maintained [28].
4. **Metering**: Gas meters are installed at the consumer delivery points and measure the volume of gas consumed, allowing utility companies to bill customers accurately.

The general flow of distribution starts at the “city gates” that lower the pressure of the received high-pressure gas from the transmission system. This gas is then distributed through the distribution pipelines to individual end users [29]. Along the distribution path, the appropriate gas pressure is maintained through regulatory stations.

The released CH_4 and CO_2 are usually related to leak emissions from pipelines and stations. However, it has been noted that an increased use of plastic piping, known for its lower emissions compared to other pipe materials, has resulted in reduced emissions of both CH_4 and CO_2.

Emissions have also been reduced by station improvements at metering and regulating (M&R) stations [29].

1.2 Blockchain Technology

Blockchain is a shared, distributed ledger that facilitates the process of recording transactions and tracking assets in a business network [30].

This **distributed ledger** can be compared to a digital record book that keeps track of these transactions, information, and assets. However, this ledger is not stored in one place, but it is duplicated and stored over many computers or devices all around the world, called **Nodes.**

The Nodes are connected to the network and all work together to maintain the ledger. Each Node participates in validating transactions, adding new data in the ledger, maintaining consensus, and ensuring decentralization. However, each of the Nodes works independently, so there's no single point of control or failure. If a node goes down, the others still have a complete copy of the ledger.

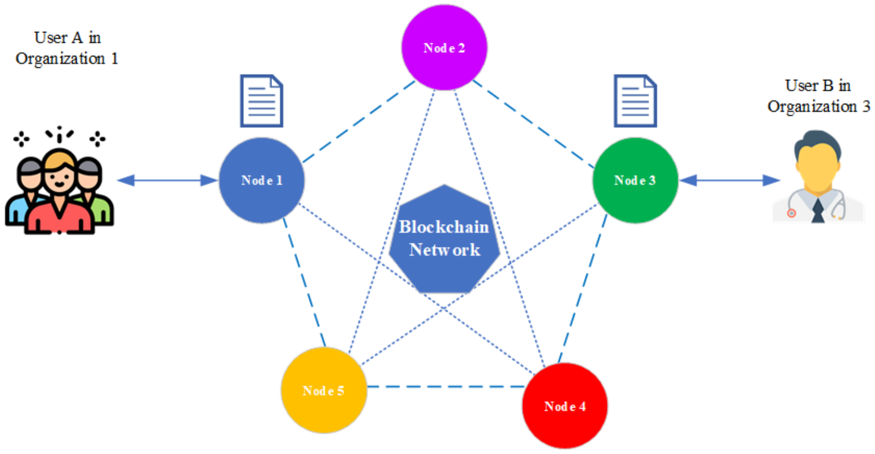


Figure 1-6: Nodes representation

This work model guarantees, as it will later be elaborated, several benefits such as:

- **Traceability**
- **Transparency**
- **Security**
- **Speed**
- **Immutability**
- **Data Accuracy**

The assets that can be stored in a Blockchain network can either be tangible like a house, a car, and cash, or intangible such as intellectual property, including patents, copyrights, and brands. Nearly any valuable entity can be monitored and exchanged via a blockchain network, leading to risk mitigation and cost reduction for all participants.

There is a common misconception that Bitcoin and Blockchain are the same. Blockchain provides the means to record and store Bitcoin transactions, but Blockchain has many uses beyond Bitcoin.

It can be compared to an operating system, like Microsoft Windows or MacOS, upon which various applications (e.g., Bitcoin) can be run. Blockchain has a wide range of potential applications in various industries such as:

- **Finance:** Blockchain can be used for trade finance, cross-border payments, and securities trading, among other things.
- **Accounting:** Blockchain can be used for auditing, tax compliance, and supply chain management, among other things.
- **Healthcare:** Blockchain can be used for managing medical records, pre-authorizing payments, and settling insurance claims.
- **Voting Systems:** Blockchain technology enhances the integrity and transparency of voting systems by ensuring that votes are securely recorded and verifiable, reducing the risk of fraud in elections.
- **Supply Chain Management:** Blockchain can be used to track and verify the origin, production, and distribution of products, ensuring transparency and authenticity within supply chains.

The main benefit of Blockchain technology is efficiency and transparency through decentralization. This means that no single person or group has control. Instead, all users collectively retain control [31].

The operation of blockchain technology and the benefits that derive by it can be clearly shown in the **car company leasing ownership** example.

Car leasing is a very complicated task to perform since it requires the cooperation of several different parties. Since the supported systems are fragmented and each party within the network maintains its own ledger, it could take days to synchronize. The operation of a traditional car leasing network is displayed in Figure 1-7.

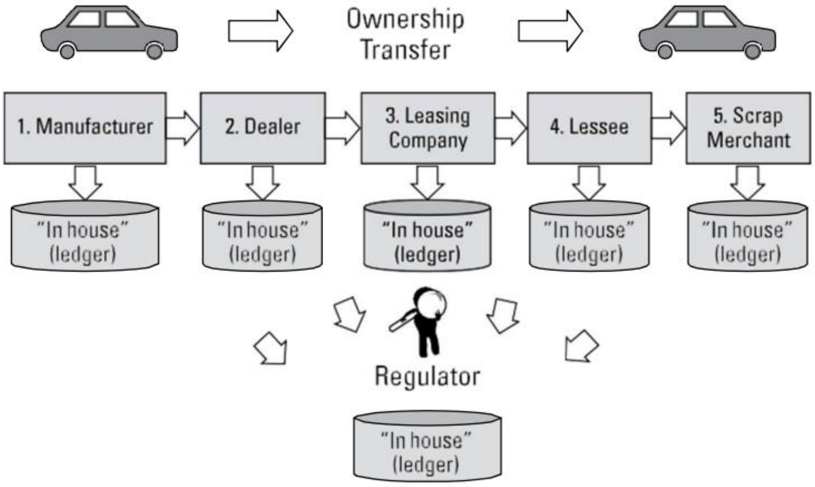


Figure 1-7: Tracking Vehicle Ownership without Blockchain.

By using Blockchain technology, a shared ledger would be created which would allow each participant to access, monitor, and analyse the state of the vehicle irrespective of where it is within its lifecycle.

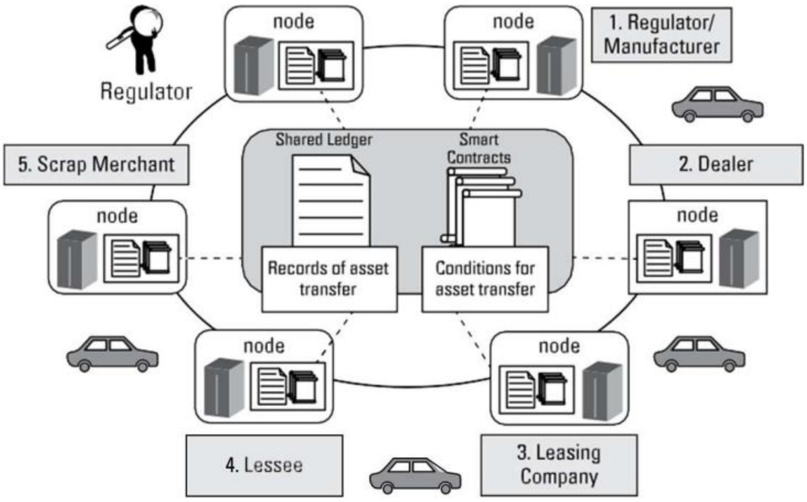


Figure 1-8: Tracking vehicle ownership with blockchain.

This blockchain system would function as follows:

1. The **government regulator** sets up and enters the details of a new vehicle registration on the blockchain. Then, the ownership of the vehicle is transferred to the manufacturer.
2. The **manufacturer** would then include the vehicle's make, model, and identification number in the vehicle template, following the rules defined in the smart contract, which is a digital agreement or rule set that manages the transaction.
3. The **dealer** can check the new stock's availability, and once a smart contract confirms the sale, ownership of the vehicle can be transferred from the manufacturer to the dealership.
4. The dealer's inventory is now visible to the **leasing company**. A transfer of ownership from the dealer to the leasing company would be again performed by a smart contract.
5. The available cars are now visible to the **lessee**, who can now complete a form requesting the execution of a lease agreement.
6. The leasing process continues between various **lessees** and the leasing company until the leasing company is ready to retire the vehicle.

By using an automated and decentralized leasing template, many benefits derive:

- **Time Saving:** Complex transactions are executed fast due to the automation of smart contracts and because verification from a central authority is not required.

- **Cost savings:**
    - Less supervision because the network is self-policed by network participants.
    - Intermediaries are reduced because participants can exchange items of value directly.
    - All participants can access the shared ledger, which eliminates the need for duplicated efforts.
- **Enhanced security:** The Blockchain's security functions protect against tampering, fraud, and cybercrime. Moreover, a permissioned network would only allow access to members who have provided proof of their identities.
- **Enhanced privacy:** By using ID's and permissions, users can specify which transactions can be visible to other participants.
- **Improved Auditability:** Since there is a single source of truth, the shared ledger, the ability to monitor and audit transactions is enhanced.

Over the next sections, the basic principles, and the architecture of blockchain technology will be presented.

1.2.1 Blockchain

By definition, "blockchain is a distributed database that maintains a continuously growing list of ordered records, called blocks. These blocks are linked using cryptography. Each block contains many parameters such as the cryptographic hash of the previous block, the timestamp, and the transaction data" [32].

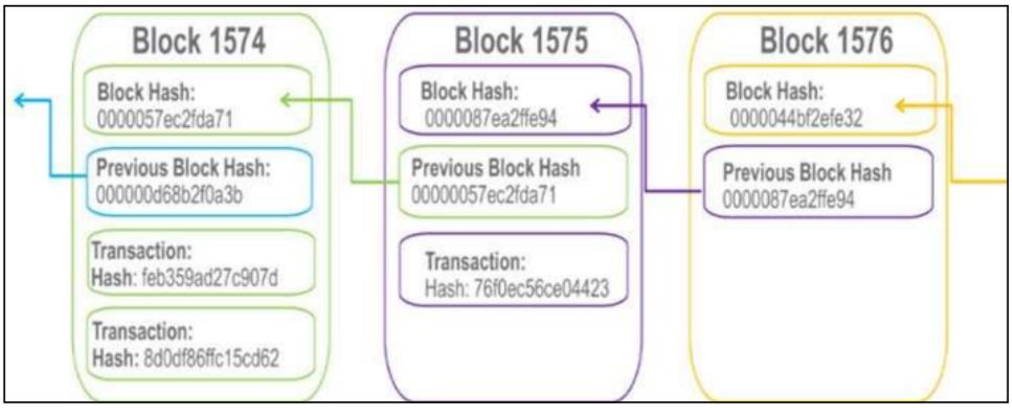
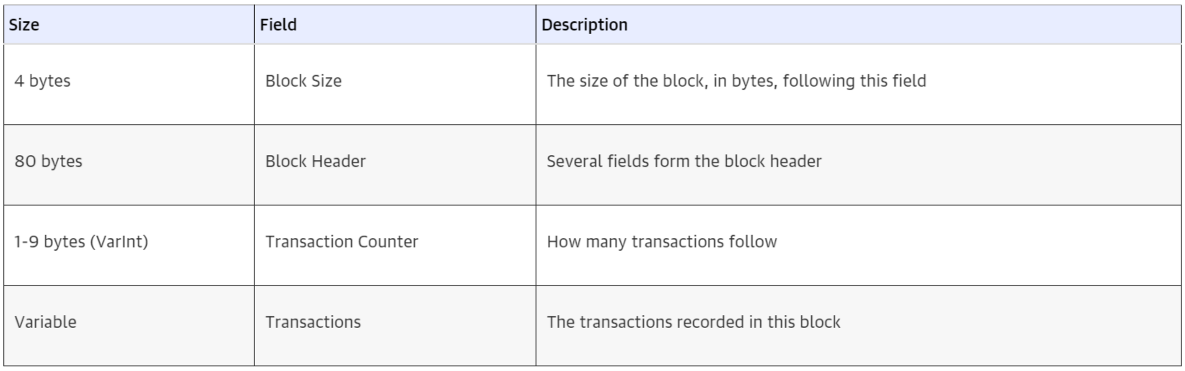


Figure 1-9: Blockchain stores transaction records in a series of connected blocks.

1.2.2 Block Structure

The block is a data container that groups transactions (explained in section 3.1) together for inclusion in the public ledger, the blockchain. According to reference [33], a block consists of a header that stores metadata and a long list of transactions that represents the body of the block. Figure 1-10 provides a list of the elements that represent the block's structure.



Size	Field	Description
4 bytes	Block Size	The size of the block, in bytes, following this field
80 bytes	Block Header	Several fields form the block header
1-9 bytes (VarInt)	Transaction Counter	How many transactions follow
Variable	Transactions	The transactions recorded in this block

Figure 1-10: Structure of a Block

Prior to explaining the different components of the blocks, it is important to explain the role of the **Block Identifiers** and how they contribute to ensuring the uniqueness of each block.

1.2.2.1. Block Identifiers

There are two different unique identifiers for Blocks: The **Block Header Hash** and **Block Height**.

Block Header Hash: This hash is a cryptographic hash, usually created by hashing the header twice through the SHA256 algorithm. This hash ensures the block's uniqueness and can be independently derived by any node by simply hashing the block header. The computation of a hash is thoroughly described in section 3.2.2.

Surprisingly, the block's hash is not included inside the block's data structure neither during the transmission of the block across the network nor when it is stored in a node's persistent storage as part of the blockchain.

Instead, each node computes the hash of the block as it is received from the network.

Block Height: This is another method to identify the block, that is based on the block's position in the blockchain. The inaugural block ever generated is situated at block height 0.

Every subsequent block added above the initial block is one position "higher" in the blockchain, like boxes stacked one on top of the other. For instance, as of September 18, 2023, the Bitcoin blockchain network has reached a block height of 808,294, indicating that it comprises a total of 808,295 blocks. The total block count equals the block height +1 since the height counting starts from 0.

In contrast to Block Hash, the Block Height is not a unique identifier. A single block always has a specific and invariant block height. However, the reverse is not true. The block height might temporarily identify two or more blocks competing for the same position in the blockchain. This usually occurs when multiple miners or nodes in the network simultaneously solve the cryptographic puzzle required to add a new block to the blockchain.

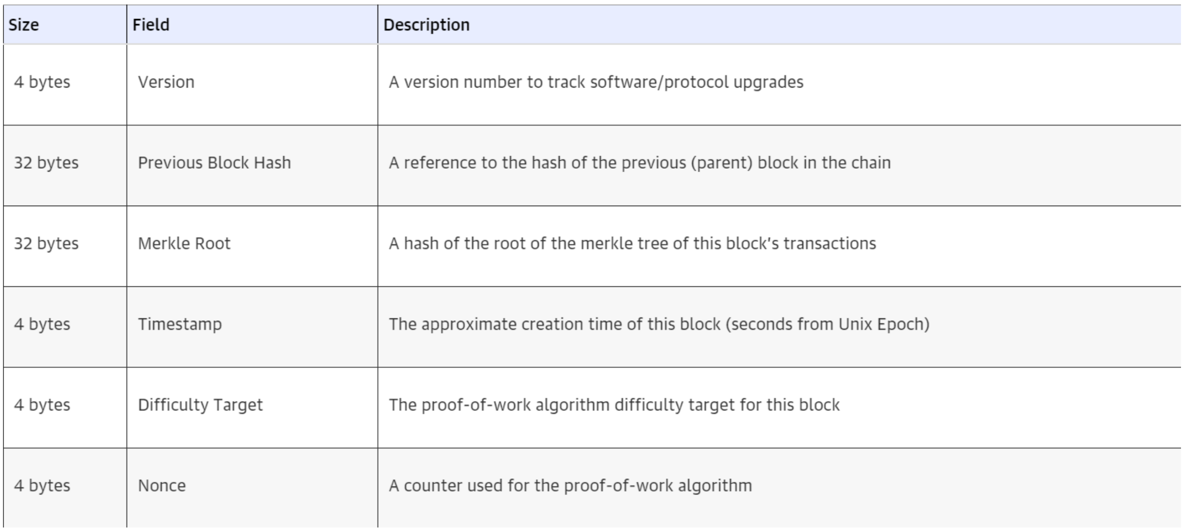
Like Block Hash, the Block Height is not part of the block's data structure. Every node automatically determines a block's position (height) in the blockchain as soon as it receives that block from the Bitcoin network.

1.2.2.2 Block Header

The block header consists of three different types of metadata:

- **Previous Block's Hash**: Connects this block to the previous block of the Blockchain.
- **Mining Metadata**: This set contains the variables of difficulty, timestamp and nonce, all of which are related to mining procedures, also known as proof of work.
- **Merkle Root**: A data structure that summarizes all the transactions in the block.

Figure 1-11 provides a list of the elements that represent the header's structure.



Size	Field	Description
4 bytes	Version	A version number to track software/protocol upgrades
32 bytes	Previous Block Hash	A reference to the hash of the previous (parent) block in the chain
32 bytes	Merkle Root	A hash of the root of the merkle tree of this block's transactions
4 bytes	Timestamp	The approximate creation time of this block (seconds from Unix Epoch)
4 bytes	Difficulty Target	The proof-of-work algorithm difficulty target for this block
4 bytes	Nonce	A counter used for the proof-of-work algorithm

Figure 1-11: Structure of the block header

Previous Block Hash: The significance of the previous block's hash stems from several key reasons:

1. **Sequential Order**: The previous block's hash, along with the rest of the header's metadata, is a vital in creating the Hash for the current block. This linkage ensures that blocks are connected in a specific sequence, creating a chronological order of transactions.

2. **Immutability**: Because each block's hash incorporates the previous block's hash, it becomes extremely difficult to alter any information in a block without changing the entire chain of subsequent blocks. This immutability is one of the key security features of blockchain technology, as it prevents tampering with past transactions.

3. **Security**: Changing a block would require recalculating its hash and the hashes of all following blocks, which would be computationally infeasible, especially in large, well-established blockchains.

Merkle Root:

Every block contains several transactions, each of which has a specific hash.

A **Merkle Tree**, also known as a binary hash tree, is a data structure used for efficiently summarizing and verifying the integrity of large sets of data [33].

In Blockchain, the Merkle Tree is used to summarize all the transactions in a block. This summary generates a digital fingerprint that represents the entire collection of transactions. This digital fingerprint is a single hash called **Merkle Root.** So, all the transaction hashes are consolidated into a single hash.

The development of the Merkle Tree is multi-level process, constructed bottom-up. For example, it is assumed that a block contains transactions A, B, C and D.

The hashes of those 4 transactions (H_A, H_B, H_C, and H_D) form the **bottom** of the tree, called the **leaves**.

Consecutive pairs of leaf nodes are then combined into parent nodes by joining the two hashes and hashing them together. For instance, the parent node H_{AB} is created by joining the hashes H_A and H_B into a single string which is then hashed.

The process continues until there is only one node at the **top**, the **Merkle Root**.

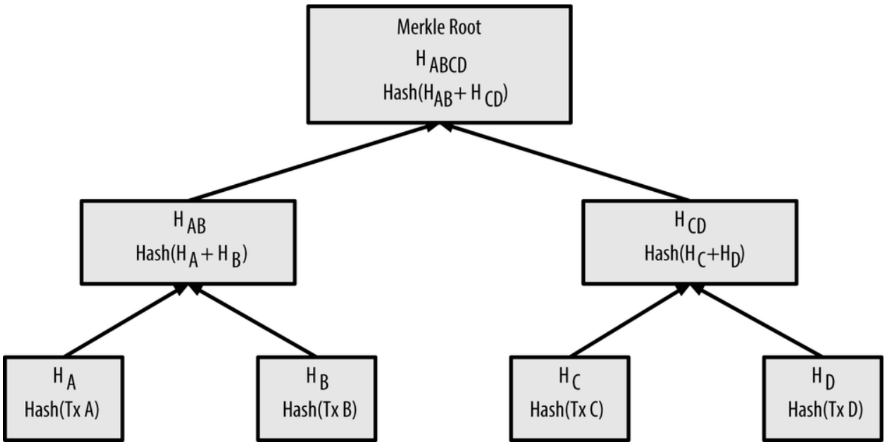


Figure 1-12: Calculation of the nodes in a Merkle Tree

It is apparent that the Merkle Tree requires an even number of leaf nodes. In cases where there's an odd number of transactions to summarize, the last transaction hash is duplicated to ensure there's an even count of leaf nodes. This ensures the tree remains balanced.

The Merkle root is included in the block's header. This means that if even one tiny detail of a transaction is altered, the Merkle root will change. Consequently, and since the metadata has been altered, the block’s hash will change thus alerting the users of the blockchain to block tampering.

Mining metadata will be further described in Section 1.2.3.1.

1.2.3 Security

So far, several key features of a blockchain network security such us cryptography and decentralization have been described. This section focuses on the presentation of other core features such as consensus mechanisms, permissions, and smart contracts.

1.2.3.1 Consensus Mechanisms

In the blockchain, a consensus mechanism is a process responsible for verifying and affirming the legitimacy of a transaction [34]. In cryptocurrencies, this mechanism creates a record of all valid coin transactions, thereby fostering trust in the coin withing the trading community. There are several mechanisms used depending on the work case such as:

- Proof of Work
- Proof of Stake
- Proof of Activity
- Proof of Authority
- Proof of Elapsed time

1.2.3.1.1 Proof of Work

Proof of Work, also known as **Mining**, is by far the most popular consensus mechanism representing about 60% of the total crypto market capitalization [35].

This method encourages network participation and validation by compensating individual nodes (miners) for contributing computational power and increasing the network's computational complexity.

As it has been described in section 1.2.2.1, adding a block to the blockchain requires the calculation of the block's hash which stems from the metadata of the block's header.

In networks that utilize Proof of Work consensus mechanisms, a valid hash should meet certain criteria. For example, a valid (or target) hash would contain several leading zeroes. The number of leading zeroes is usually referred as **difficulty**.

Finding a valid hash would be a computing intensive process that requires miners to test many hashes before finding the valid. Miners run scripts that perform numerous iterations producing different hashes. At each iteration a variable called **nonce,** which belongs to the block's header, is modified therefore producing a different hash.

All miners are competing against each other till someone finds a valid hash. Then the addition of the block to the blockchain gets validated and the miner gets rewarded. As of 2023, network participants who validate transactions are awarded 6.25 bitcoins (BTC) for each block successfully mined [36]. As of the 19th of September 2023, 6.25 BTC equals 169.540,63 USD.

By using Proof of Work many security benefits arise:

- It becomes extremely expensive for malicious actors to launch attacks, such as double spending or rewriting transaction history, as it would require an overwhelming amount of computational power.
- Dishonest participants cannot manipulate the ledger, as they would need to control a majority of the network's computational power, which is highly impractical and costly.
- Once a block is added to the blockchain, it becomes increasingly difficult to alter or replace it.

However, Proof of Work imposes on substantial disadvantage: It consumes a significant amount of energy. As reference [37] suggests, it is estimated that the entire blockchain network's PoW mechanism uses energy equivalent to the total consumption of Thailand.

1.2.3.1.2 Proof of Stake

Proof-of-stake reduces the amount of computational work needed to verify blocks and transactions. It changes the process of verifying blocks by leveraging the machines of coin owners, minimizing the need of extensive computational resources. Here's how PoS works:

- **Collateral**: Coin owners offer their cryptocurrency holdings as collateral, a process known as staking. By doing so, they become eligible to participate in the validation of blocks and earn rewards.
- **Validators:** The "miners" of PoW are now called validators. They are selected randomly from the pool of coin holders.
- **Transaction Confirmation:** Validators, once chosen, confirm the validity of transactions and verify the information in blocks.
- **Fee Collection:** Validators also can collect transaction fees as part of their reward for participating in block validation.

Many benefits arise from the utilization of this consensus mechanism:

- **Reduced Energy Consumption:** It doesn't require the resource-intensive mining processes of PoW.
- **Security Through Ownership:** The participants with a financial stake in the network will act in its best interests.

1.2.3.1.3 Proof of Activity

This mechanism blends elements of both Proof of Work (PoW) and Proof of Stake (PoS) by utilizing their strengths.

Initially, PoA operates like PoW, but after the completion of a new block, it transitions to operate like a PoS mechanism.

1.2.3.1.4 Proof of Authority

This consensus mechanism was developed by organizations and private companies. Withing this system, the transactions are approved by validators, who possess verified accounts.

These validators are required to disclose their real identities as a prerequisite for validating transactions.

1.2.3.1.5 Proof of Elapsed Time

This mechanism was created by Intel to permit blockchain to decide the person who will create the next block by using a lottery system.

As a result, this approach provides an opportunity for all traders to participate in the creation of the next block. It offers an efficient process that requires fewer resources and consumes less energy.

1.2.3.2 Permissioned Networks

Permissioned blockchains are blockchain networks that require access to be a part of [38].

Usually serving the needs of private corporations or organizations, permissioned blockchains are developed to take advantage of blockchain without sacrificing the authority aspect of a centralized system.

In this type of networks, the ledger administrators are responsible for allowing clearance and rights to the user. The administrators [39]:

- Assign roles to permissioned users, that dictate what information a user would be able to access.
- Delimit the framework of the rights and responsibilities of the permissioned users.
- Require that the permission users be authenticated through certificates or digital identifier methods.

Various advantages and disadvantages arise from the use of permissioned networks:

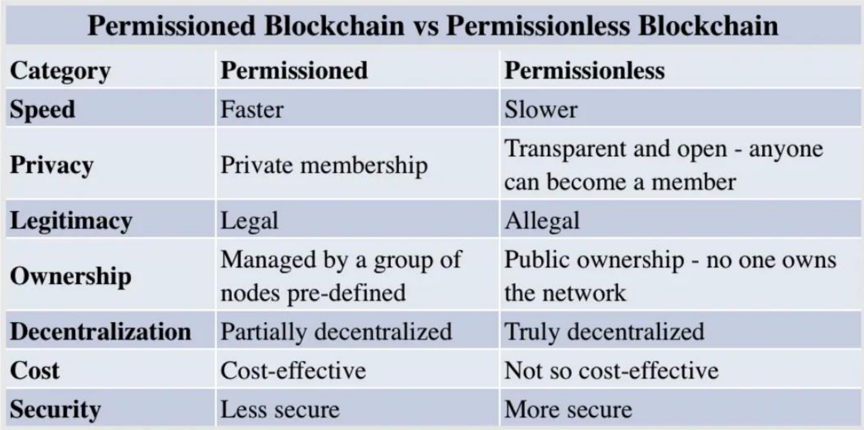
Benefits:

- **Efficient performance:** The limited number of nodes on the platform along with a pre-determined consensus system that relies on specific nodes for validating a transaction lead to improved overall performance.
- **Proper governance structure:** These networks have a clear hierarchy providing an appropriate governance structure. The administrators determine the rules of the network and update them regularly.
- **Decentralized Storage:** Permissioned networks also make proper use of the decentralized nature of blockchain for data storage.
- **Cost-Effective:** The permissioned networks are more cost-effective in comparison to permissionless blockchains.

Disadvantages:

- **Compromised Security:** There are instances where a small group of permissioned members can work together to tamper data.
- **Control, Censorship and Regulation:** There are cases where the system administrators might restrict a transaction or control it from happening, bringing censorship to the network.

Figure 1-13 demonstrates the key differences between permissioned and permissionless blockchain systems.



Permissioned Blockchain vs Permissionless Blockchain

Category	Permissioned	Permissionless
Speed	Faster	Slower
Privacy	Private membership	Transparent and open - anyone can become a member
Legitimacy	Legal	Allegal
Ownership	Managed by a group of nodes pre-defined	Public ownership - no one owns the network
Decentralization	Partially decentralized	Truly decentralized
Cost	Cost-effective	Not so cost-effective
Security	Less secure	More secure

Figure 1-13: Differences between permissioned and permissionless networks

1.2.3.3 Smart Contracts

A smart contract is a self-executing program that automates the actions specified in an agreement or contract. The set of transactions stimulated by the smart contract are trackable and irreversible [40].

Smart contracts enable secure and trusted transactions and agreements among unrelated and anonymous parties, all without the need of a central authority, legal system, or external enforcement mechanism.

Smart contracts find several uses. The most common use is ensuring transactions between two parties, such as the purchase and delivery of goods.

For example, it is assumed that a smart contract is established between a manufacturer and a supplier. In this arrangement, the manufacturer is accountable for making payments for the goods, while the supplier is responsible for arranging the delivery of the goods.

The execution of this smart contract occurs upon the successful delivery of the goods. Consequently, once the supplier completes the delivery, they will instantly receive the funds as specified in the contract.

This automated process guarantees that both parties meet their obligations without the need for intermediaries or manual interventions.

Several benefits and downfalls arise from the use of smart contracts:

Benefits:

- **Efficiency:** Fast contract execution
- **Accuracy:** Absence of human errors in the application of the contract
- **Immutability:** The programming cannot be altered

Downfalls:

- **Permanent:** Smart contracts cannot be changed if there are mistakes
- **Human factor:** The human factor comes into play as programmers are responsible for ensuring that the code accurately reflects the terms of the contract.
- **Loopholes:** Loopholes can exist within the code, allowing for contracts to be executed in bad faith.

1.2.4 Regulatory and Legal Considerations of Blockchain

Several legal considerations arise from the use of blockchain technology:

1. **Data Privacy and Protection:** The decentralized and immutable nature of storing data in blockchain technology raises questions about compliance with GDPR regulations (General Data Protection Regulation). These concerns are related to the way that personal and sensitive information is being handled.
2. **Cross-Border Transactions:** When a transaction is performed between two parties that belong into different jurisdictions, the compliance with international laws and regulations might be challenging.
3. **Smart Contracts:** There are great discrepancies between the legal status of smart contracts across jurisdictions.
4. **Taxation:** Taxation of cryptocurrency transactions and assets is a complex issue. Regulations concerning capital gains, reporting requirements, and tax treatment differ by country and may evolve over time.
5. **Recordkeeping and Auditing:** Since blockchain’s immutability makes it challenging to rectify errors in transaction data, innovative solutions might be needed to ensure compliance with recordkeeping and auditing.

To tackle the issues mentioned above, collaboration between blockchain innovators, legal experts, and regulatory authorities is critical.

1.2.5 Environmental Impact

On of the most significant concerns that derive from the use of blockchain technology is the energy consumption required to power the decentralized network of computers that make up the blockchain [41].

To be more precise, a substantial portion of this energy consumption can be attributed to the mining process, which operates on the proof of work consensus mechanism.

According to a report by PwC, the energy consumption necessary to sustain the Bitcoin network is comparable to the energy usage of the entire nation of Switzerland.

According to a study by the university of Cambridge, the annual energy consumption of Bitcoin mining is estimated to be around 121 TWh, which is equivalent to the energy consumption of Argentina.

Another environmental concern is the generation of electronic waste due to the obsolescence of mining hardware.

As blockchain networks develop and become more complex, mining becomes increasingly challenging and demands greater computational capabilities. This results in older mining equipment becoming outdated, which is often discarded.

As a result, an accumulation of a substantial volume of electronic waste has been observed, posing potential environmental hazards if not adequately managed.

These concerns have incentivized companies to mitigate the environmental impact of blockchain by:

- Transitioning blockchain networks to more energy-efficient consensus mechanisms, such as proof-of-stake.
- Exploring the use of renewable energy to power blockchain operations.

In addition to these immediate reforms, blockchain can provide solution to several environmental issues by:

- Carbon credit tracking
- Supply chain transparency
- Renewable energy trading

The implementation of these reforms strongly aligns with the objectives of this thesis, which seeks to establish an effective blockchain-enabled emissions management system within the natural gas supply chain.

Chapter 2 : Methodology

The methodology aims at laying the foundation upon which the Blockchain Application will be developed. It consists of several sections such as:

1. **Natural Gas Lifecycle Mapping:** Identification of the main pollution-producing processes involved in natural gas extraction, processing, and distribution. These processes will be the core of the blockchain application that will be later developed.
2. **Thorough description of the multi-tier architecture.**
3. **Arrangement of identified pollutants in a multi-tier architecture:** Demonstration of how the natural gas supply chain can be imprinted in such an arrangement.
4. **Creation of the architecture that will be implemented in the Blockchain Application:** This architecture is based on specific emissions data from the EPA reports, which will be ranked in tiers.

2.1 Natural Gas Lifecycle Mapping

As described in the introductory chapters of this thesis, natural gas extraction, processing and distribution can be a complex and multidimensional process. As a result of the variating composition of natural gas depending on its source of origin, there are large discrepancies in its refining requirements. Therefore, the great differences between the Natural Gas's production lines made it particularly demanding to find a unified approach.

It was decided that the unified mapping be based on EPA's (U.S Environmental Protection Agency) paper **"Inventory of U.S Greenhouse Gas Emissions and Sinks"** [42]. This paper presents all the different processes that cause emissions during natural gas lifecycle. It also provides collected data of the emissions from each process through years 1990-2021.

In addition, this case study focuses on the information provided in section **"Natural Gas Systems (CRF Source Category 1B2b)"**. The section provides information on the total greenhouse gas emissions (CH_4, CO_2, and N_2O) from natural gas systems in the United States, including emissions from leaks, venting, and flaring. The data presented in the section is based on calculations and estimates made by the EPA using various data sources and methodologies. More specifically these emissions were calculated using a combination of activity data and emission factors. The activity data includes information on the amount of natural gas produced, processed, transmitted, distributed, and consumed, as well as the number and type of equipment used in each segment of the natural gas system. The emission factors are estimates of the amount of greenhouse gases emitted per unit of activity, and they are based on a combination of direct measurements, engineering calculations, and modelling.

An in-depth analysis is provided in "**Annex 3.6: Methodology for Estimating CH_4, CO_2, and N_2O Emissions from Natural Gas Systems**" [29]. More specifically the Annex provides the following set of data:

- Full time series of emissions data.
- Activity data.
- Emission factors.
- Additional information on methods and data sources used to estimate greenhouse gas emissions.

The Annex is divided into 2 different sections:

1. **Total** CH_4, CO_2, and N_2O Emissions in kilotons [kt] for Natural Gas Systems by Segment, Source, and Year (1990-2021)
2. Specific CH_4 and CO_2 Emissions [kt] for Select Natural Gas Systems Onshore Production Sources **per U.S Basin**

2.1.1 Total US GHG Emissions (CH4, CO2, N2O) from Natural Gas Systems

According to [42], natural gas lifecycle consists of 6 main stages of processing:

1. Exploration
2. Production
3. Processing
4. Transmission and Storage
5. Distribution
6. Other

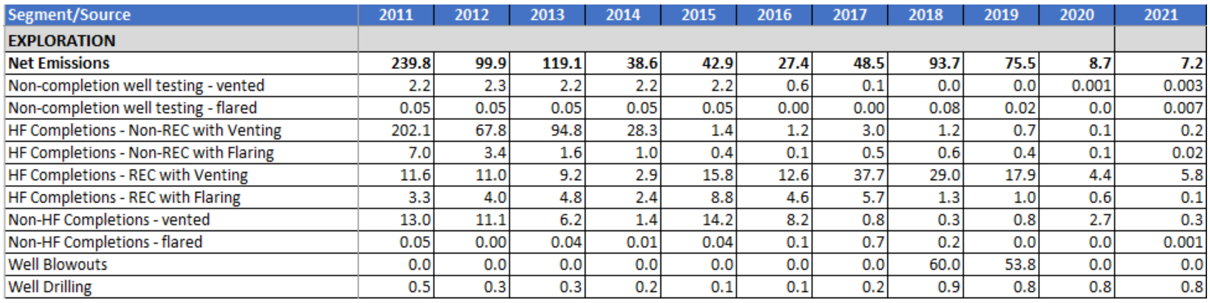
The figures presented in Sections 2.1.1.1 - 2.1.1.5 contain the CH_4 emissions in kilotons [kt] grouped by emissions segments and sources for years 1990 - 2021. The CO_2 and N_2O emissions for the same segments can be found in the "2023_ghgi_natural_gas_systems_annex36_tables" excel.

2.1.1.1 Exploration

The exploration stage of natural gas systems includes well drilling, testing, and completion. During this stage, companies drill wells to explore for natural gas deposits and then test the wells to determine their productivity. If the well is productive, it is completed, which involves installing equipment to allow the gas to flow from the well to the surface.

During this stage the occurring greenhouse gas emissions include methane (CH_4) and carbon dioxide (CO_2) emissions from leaks, vents, and flaring. However, as the report mentions, the emissions from this stage are relatively small compared to other stages of natural gas systems, accounting for less than 0.2% of CH_4 emissions and CO_2 emissions from natural gas systems in 2021.

More specifically, the greenhouse gas emissions that arise from these processes are presented in the Figure 2-1:



Segment/Source	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
EXPLORATION											
Net Emissions	**239.8**	**99.9**	**119.1**	**38.6**	**42.9**	**27.4**	**48.5**	**93.7**	**75.5**	**8.7**	**7.2**
Non-completion well testing - vented	2.2	2.3	2.2	2.2	2.2	0.6	0.1	0.0	0.0	0.001	0.003
Non-completion well testing - flared	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.08	0.02	0.0	0.007
HF Completions - Non-REC with Venting	202.1	67.8	94.8	28.3	1.4	1.2	3.0	1.2	0.7	0.1	0.2
HF Completions - Non-REC with Flaring	7.0	3.4	1.6	1.0	0.4	0.1	0.5	0.6	0.4	0.1	0.02
HF Completions - REC with Venting	11.6	11.0	9.2	2.9	15.8	12.6	37.7	29.0	17.9	4.4	5.8
HF Completions - REC with Flaring	3.3	4.0	4.8	2.4	8.8	4.6	5.7	1.3	1.0	0.6	0.1
Non-HF Completions - vented	13.0	11.1	6.2	1.4	14.2	8.2	0.8	0.3	0.8	2.7	0.3
Non-HF Completions - flared	0.05	0.00	0.04	0.01	0.04	0.1	0.7	0.2	0.0	0.0	0.001
Well Blowouts	0.0	0.0	0.0	0.0	0.0	0.0	0.0	60.0	53.8	0.0	0.0
Well Drilling	0.5	0.3	0.3	0.2	0.1	0.1	0.2	0.9	0.8	0.8	0.8

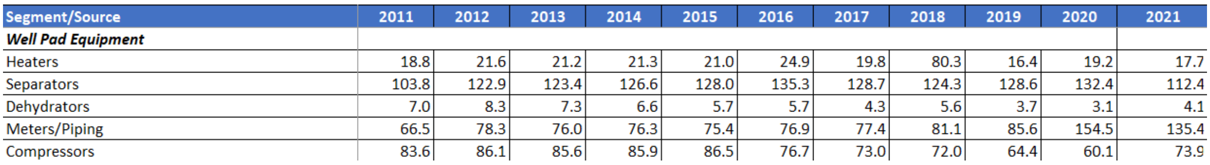
Figure 2-1: Emissions from Exploration

2.1.1.2 Production

The production segment involves extracting raw gas from underground formations through wells. Emissions occur during this process, including emissions from the wells themselves, as well as from equipment and activities at the well-site such as pneumatic controllers, tanks, separators, and liquids unloading. The gathering and boosting sources, which include gathering stations and pipelines, are also part of the production sector. These stations receive natural gas from production sites and transfer it via gathering pipelines to transmission pipelines or processing facilities.

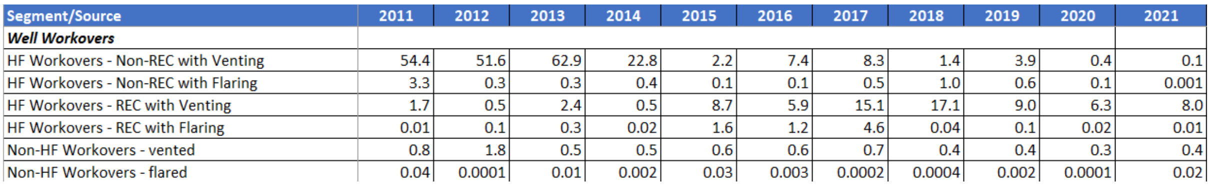
In 2021, emissions from the production segment accounted for 52% of methane (CH_4) emissions and 25% of carbon dioxide (CO_2) emissions from natural gas systems. The major sources of methane emissions within the production segment were gathering and boosting, particularly from compressor exhaust slip, compressor venting and leaks, and tanks. Flaring accounted for most of the CO_2 emissions from production, with the highest emissions coming from flare stacks at gathering stations, miscellaneous onshore production flaring, and tank flaring.

More specifically, the greenhouse gas emissions that arise from these processes are presented in the Figures 2.2 – 2.9:



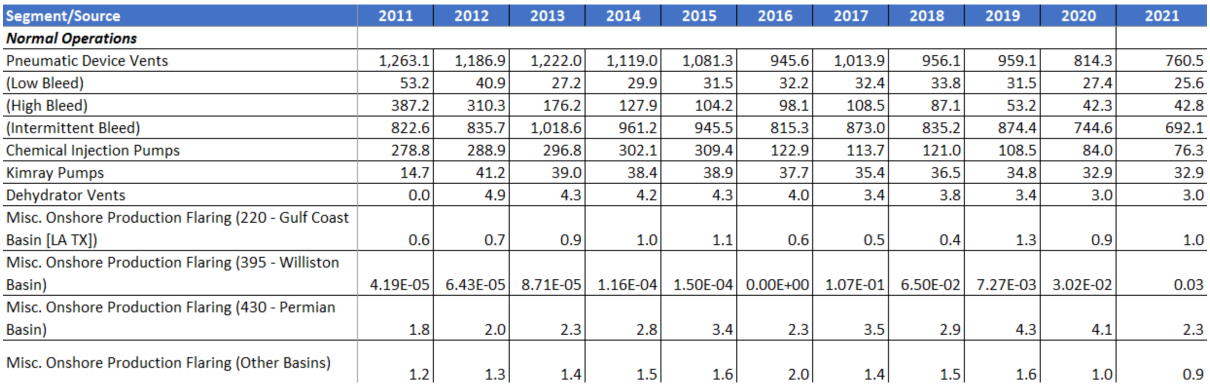
Segment/Source	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Well Pad Equipment											
Heaters	18.8	21.6	21.2	21.3	21.0	24.9	19.8	80.3	16.4	19.2	17.7
Separators	103.8	122.9	123.4	126.6	128.0	135.3	128.7	124.3	128.6	132.4	112.4
Dehydrators	7.0	8.3	7.3	6.6	5.7	5.7	4.3	5.6	3.7	3.1	4.1
Meters/Piping	66.5	78.3	76.0	76.3	75.4	76.9	77.4	81.1	85.6	154.5	135.4
Compressors	83.6	86.1	85.6	85.9	86.5	76.7	73.0	72.0	64.4	60.1	73.9

Figure 2-2: Emissions from Well Pad Equipment



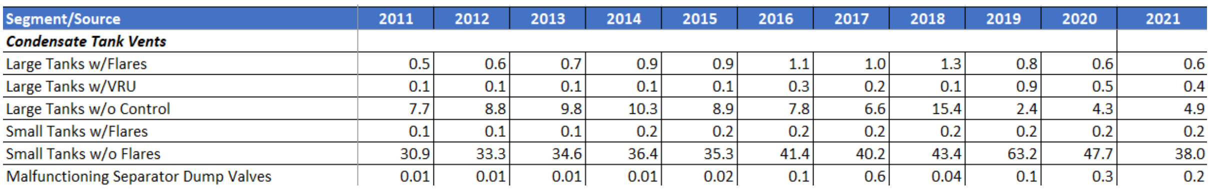
Segment/Source	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Well Workovers											
HF Workovers - Non-REC with Venting	54.4	51.6	62.9	22.8	2.2	7.4	8.3	1.4	3.9	0.4	0.1
HF Workovers - Non-REC with Flaring	3.3	0.3	0.3	0.4	0.1	0.1	0.5	1.0	0.6	0.1	0.001
HF Workovers - REC with Venting	1.7	0.5	2.4	0.5	8.7	5.9	15.1	17.1	9.0	6.3	8.0
HF Workovers - REC with Flaring	0.01	0.1	0.3	0.02	1.6	1.2	4.6	0.04	0.1	0.02	0.01
Non-HF Workovers - vented	0.8	1.8	0.5	0.5	0.6	0.6	0.7	0.4	0.4	0.3	0.4
Non-HF Workovers - flared	0.04	0.0001	0.01	0.002	0.03	0.003	0.0002	0.0004	0.002	0.0001	0.02

Figure 2-3: Emissions from Well Workovers



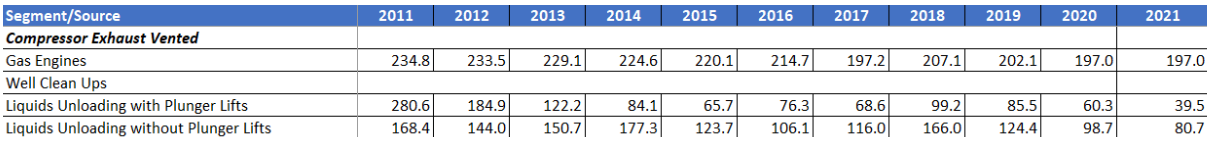
Segment/Source	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Normal Operations											
Pneumatic Device Vents	1,263.1	1,186.9	1,222.0	1,119.0	1,081.3	945.6	1,013.9	956.1	959.1	814.3	760.5
(Low Bleed)	53.2	40.9	27.2	29.9	31.5	32.2	32.4	33.8	31.5	27.4	25.6
(High Bleed)	387.2	310.3	176.2	127.9	104.2	98.1	108.5	87.1	53.2	42.3	42.8
(Intermittent Bleed)	822.6	835.7	1,018.6	961.2	945.5	815.3	873.0	835.2	874.4	744.6	692.1
Chemical Injection Pumps	278.8	288.9	296.8	302.1	309.4	122.9	113.7	121.0	108.5	84.0	76.3
Kimray Pumps	14.7	41.2	39.0	38.4	38.9	37.7	35.4	36.5	34.8	32.9	32.9
Dehydrator Vents	0.0	4.9	4.3	4.2	4.3	4.0	3.4	3.8	3.4	3.0	3.0
Misc. Onshore Production Flaring (220 - Gulf Coast Basin [LA TX])	0.6	0.7	0.9	1.0	1.1	0.6	0.5	0.4	1.3	0.9	1.0
Misc. Onshore Production Flaring (395 - Williston Basin)	4.19E-05	6.43E-05	8.71E-05	1.16E-04	1.50E-04	0.00E+00	1.07E-01	6.50E-02	7.27E-03	3.02E-02	0.03
Misc. Onshore Production Flaring (430 - Permian Basin)	1.8	2.0	2.3	2.8	3.4	2.3	3.5	2.9	4.3	4.1	2.3
Misc. Onshore Production Flaring (Other Basins)	1.2	1.3	1.4	1.5	1.6	2.0	1.4	1.5	1.6	1.0	0.9

Figure 2-4: Emissions from Normal Operations



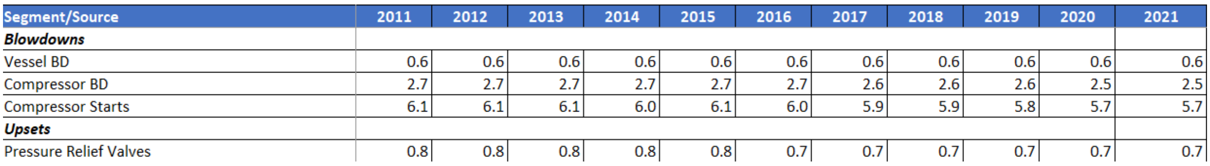
Segment/Source	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Condensate Tank Vents											
Large Tanks w/Flares	0.5	0.6	0.7	0.9	0.9	1.1	1.0	1.3	0.8	0.6	0.6
Large Tanks w/VRU	0.1	0.1	0.1	0.1	0.1	0.3	0.2	0.1	0.9	0.5	0.4
Large Tanks w/o Control	7.7	8.8	9.8	10.3	8.9	7.8	6.6	15.4	2.4	4.3	4.9
Small Tanks w/Flares	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Small Tanks w/o Flares	30.9	33.3	34.6	36.4	35.3	41.4	40.2	43.4	63.2	47.7	38.0
Malfunctioning Separator Dump Valves	0.01	0.01	0.01	0.01	0.02	0.1	0.6	0.04	0.1	0.3	0.2

Figure 2-5: Emissions from Condensate Tank Vents



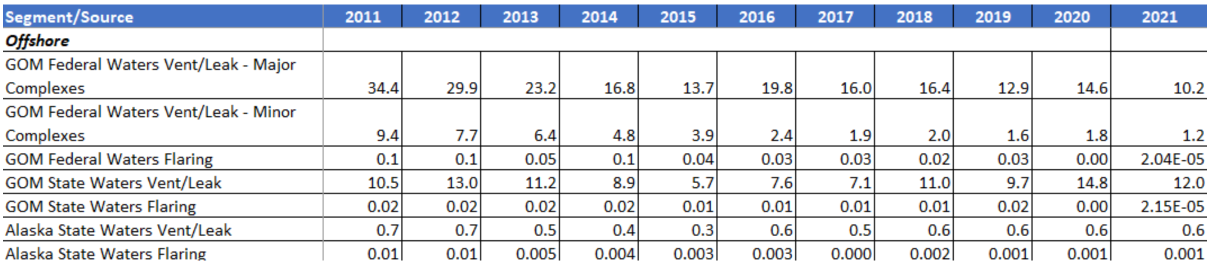
Segment/Source	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Compressor Exhaust Vented											
Gas Engines	234.8	233.5	229.1	224.6	220.1	214.7	197.2	207.1	202.1	197.0	197.0
Well Clean Ups											
Liquids Unloading with Plunger Lifts	280.6	184.9	122.2	84.1	65.7	76.3	68.6	99.2	85.5	60.3	39.5
Liquids Unloading without Plunger Lifts	168.4	144.0	150.7	177.3	123.7	106.1	116.0	166.0	124.4	98.7	80.7

Figure 2-6: Vented Emissions from Compressor Exhaust



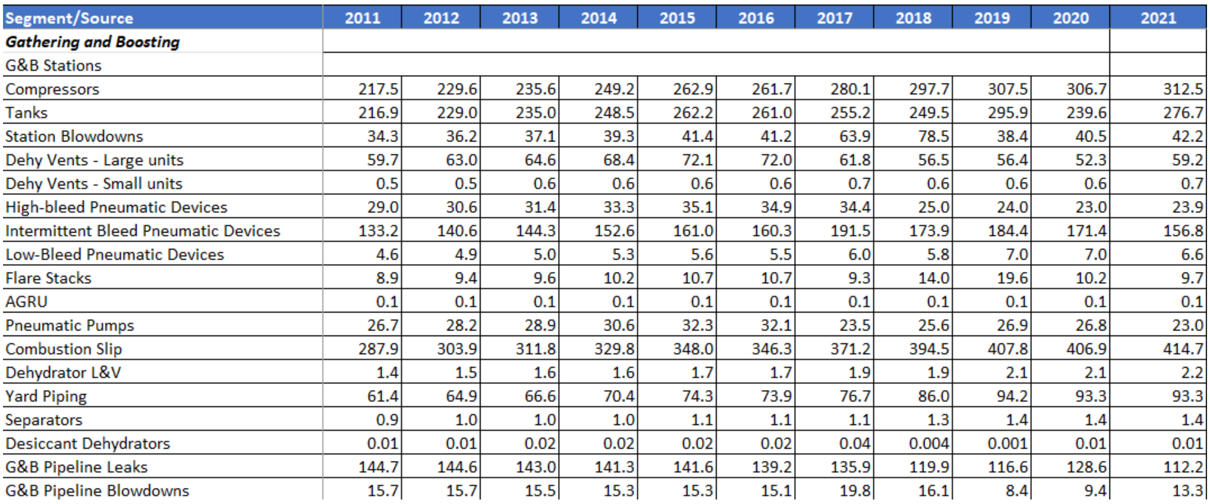
Segment/Source	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Blowdowns											
Vessel BD	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Compressor BD	2.7	2.7	2.7	2.7	2.7	2.7	2.6	2.6	2.6	2.5	2.5
Compressor Starts	6.1	6.1	6.1	6.0	6.1	6.0	5.9	5.9	5.8	5.7	5.7
Upsets											
Pressure Relief Valves	0.8	0.8	0.8	0.8	0.8	0.7	0.7	0.7	0.7	0.7	0.7

Figure 2-7: Emissions from Blowdowns & Upsets



Segment/Source	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Offshore											
GOM Federal Waters Vent/Leak - Major Complexes	34.4	29.9	23.2	16.8	13.7	19.8	16.0	16.4	12.9	14.6	10.2
GOM Federal Waters Vent/Leak - Minor Complexes	9.4	7.7	6.4	4.8	3.9	2.4	1.9	2.0	1.6	1.8	1.2
GOM Federal Waters Flaring	0.1	0.1	0.05	0.1	0.04	0.03	0.03	0.02	0.03	0.00	2.04E-05
GOM State Waters Vent/Leak	10.5	13.0	11.2	8.9	5.7	7.6	7.1	11.0	9.7	14.8	12.0
GOM State Waters Flaring	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.02	0.00	2.15E-05
Alaska State Waters Vent/Leak	0.7	0.7	0.5	0.4	0.3	0.6	0.5	0.6	0.6	0.6	0.6
Alaska State Waters Flaring	0.01	0.01	0.005	0.004	0.003	0.003	0.000	0.002	0.001	0.001	0.001

Figure 2-8: Emissions from Offshore Plant Systems



Segment/Source	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Gathering and Boosting											
G&B Stations											
Compressors	217.5	229.6	235.6	249.2	262.9	261.7	280.1	297.7	307.5	306.7	312.5
Tanks	216.9	229.0	235.0	248.5	262.2	261.0	255.2	249.5	295.9	239.6	276.7
Station Blowdowns	34.3	36.2	37.1	39.3	41.4	41.2	63.9	78.5	38.4	40.5	42.2
Dehy Vents - Large units	59.7	63.0	64.6	68.4	72.1	72.0	61.8	56.5	56.4	52.3	59.2
Dehy Vents - Small units	0.5	0.5	0.6	0.6	0.6	0.6	0.7	0.6	0.6	0.6	0.7
High-bleed Pneumatic Devices	29.0	30.6	31.4	33.3	35.1	34.9	34.4	25.0	24.0	23.0	23.9
Intermittent Bleed Pneumatic Devices	133.2	140.6	144.3	152.6	161.0	160.3	191.5	173.9	184.4	171.4	156.8
Low-Bleed Pneumatic Devices	4.6	4.9	5.0	5.3	5.6	5.5	6.0	5.8	7.0	7.0	6.6
Flare Stacks	8.9	9.4	9.6	10.2	10.7	10.7	9.3	14.0	19.6	10.2	9.7
AGRU	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Pneumatic Pumps	26.7	28.2	28.9	30.6	32.3	32.1	23.5	25.6	26.9	26.8	23.0
Combustion Slip	287.9	303.9	311.8	329.8	348.0	346.3	371.2	394.5	407.8	406.9	414.7
Dehydrator L&V	1.4	1.5	1.6	1.6	1.7	1.7	1.9	1.9	2.1	2.1	2.2
Yard Piping	61.4	64.9	66.6	70.4	74.3	73.9	76.7	86.0	94.2	93.3	93.3
Separators	0.9	1.0	1.0	1.0	1.1	1.1	1.1	1.3	1.4	1.4	1.4
Desiccant Dehydrators	0.01	0.01	0.02	0.02	0.02	0.02	0.04	0.004	0.001	0.01	0.01
G&B Pipeline Leaks	144.7	144.6	143.0	141.3	141.6	139.2	135.9	119.9	116.6	128.6	112.2
G&B Pipeline Blowdowns	15.7	15.7	15.5	15.3	15.3	15.1	19.8	16.1	8.4	9.4	13.3

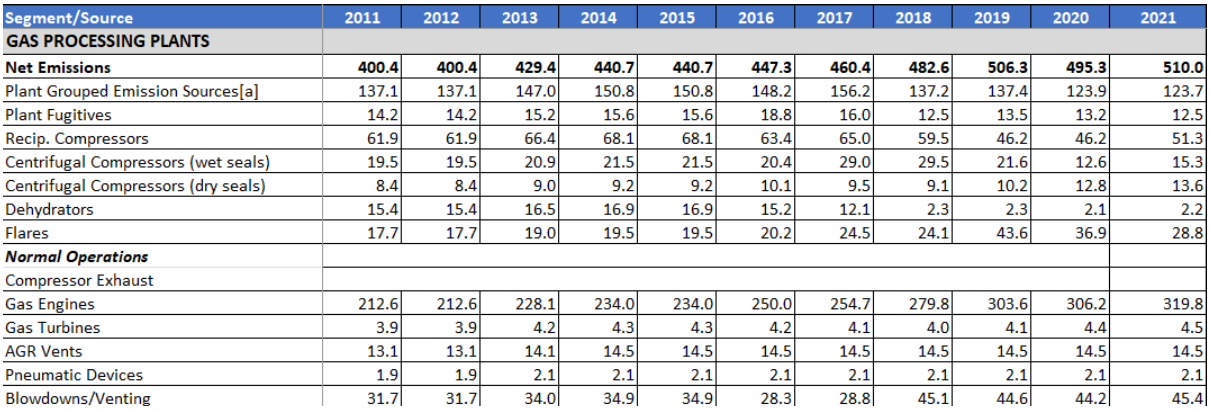
Figure 2-9: Emissions from Gathering and Boosting

2.1.1.3 Processing Plants

The processing segment of natural gas operations involves the removal of natural gas liquids and other constituents from raw gas, resulting in "pipeline quality" gas for transmission. The primary methane emissions during this stage come from compressors, including compressor seals. Most of the total CO_2 emissions arise from acid gas removal (AGR) units. Processing plants contributed to 8% of CH_4 emissions and 72% of CO_2 emissions from natural gas systems.

Over the years, methane emissions from processing have seen a decline of 40% from 1990 to 2021, mainly due to reduced emissions from compressors (leaks and venting) and equipment leaks. However, methane emissions increased by 3% from 2020 to 2021 because of elevated emissions from gas engines.

Carbon dioxide emissions from processing decreased by 8% from 1990 to 2021, primarily attributed to a reduction in AGR emissions. Nevertheless, CO_2 emissions increased by 3% from 2020 to 2021 due to higher emissions from AGR. Nitrous oxide emissions decreased by 1% from 2020 to 2021.



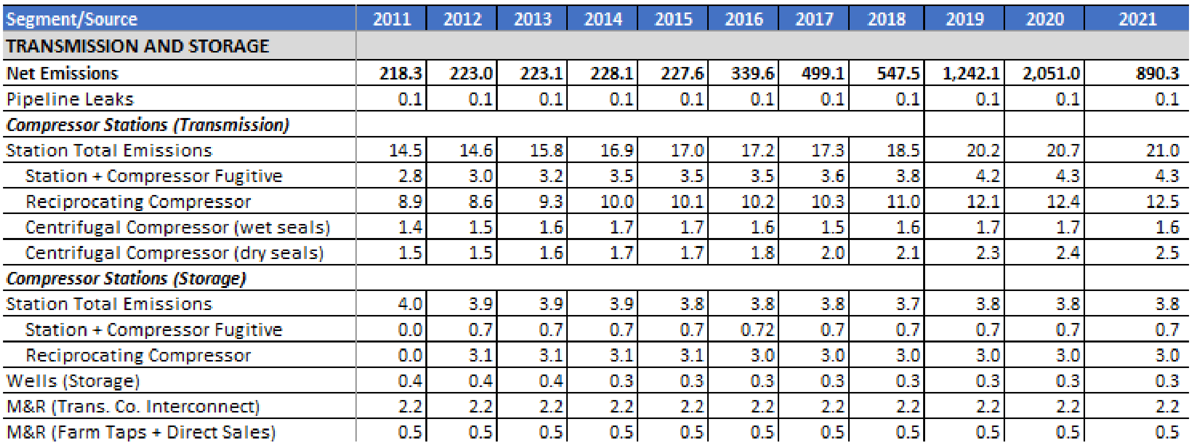
Segment/Source	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
GAS PROCESSING PLANTS											
Net Emissions	**400.4**	**400.4**	**429.4**	**440.7**	**440.7**	**447.3**	**460.4**	**482.6**	**506.3**	**495.3**	**510.0**
Plant Grouped Emission Sources[a]	137.1	137.1	147.0	150.8	150.8	148.2	156.2	137.2	137.4	123.9	123.7
Plant Fugitives	14.2	14.2	15.2	15.6	15.6	18.8	16.0	12.5	13.5	13.2	12.5
Recip. Compressors	61.9	61.9	66.4	68.1	68.1	63.4	65.0	59.5	46.2	46.2	51.3
Centrifugal Compressors (wet seals)	19.5	19.5	20.9	21.5	21.5	20.4	29.0	29.5	21.6	12.6	15.3
Centrifugal Compressors (dry seals)	8.4	8.4	9.0	9.2	9.2	10.1	9.5	9.1	10.2	12.8	13.6
Dehydrators	15.4	15.4	16.5	16.9	16.9	15.2	12.1	2.3	2.3	2.1	2.2
Flares	17.7	17.7	19.0	19.5	19.5	20.2	24.5	24.1	43.6	36.9	28.8
Normal Operations											
Compressor Exhaust											
Gas Engines	212.6	212.6	228.1	234.0	234.0	250.0	254.7	279.8	303.6	306.2	319.8
Gas Turbines	3.9	3.9	4.2	4.3	4.3	4.2	4.1	4.0	4.1	4.4	4.5
AGR Vents	13.1	13.1	14.1	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5
Pneumatic Devices	1.9	1.9	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1
Blowdowns/Venting	31.7	31.7	34.0	34.9	34.9	28.3	28.8	45.1	44.6	44.2	45.4

Figure 2-10: Emissions from Normal Operations of Gas Processing Plants

2.1.1.4 Transmission and Storage

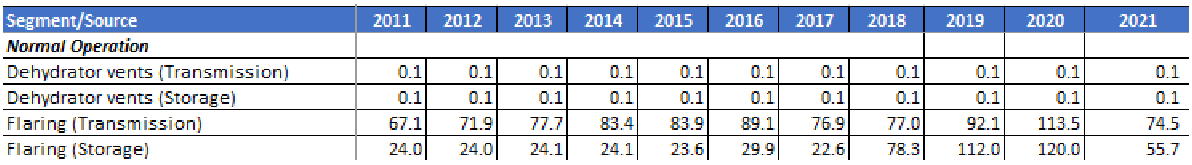
The natural gas transmission and storage segment involves high-pressure pipelines and compressor stations that transport gas over long distances. Methane emissions from compressor stations and pneumatic controllers, along with venting and exhaust emissions, are the main contributors to greenhouse gas emissions in this stage.

Methane emissions from this segment decreased by 30% from 1990 to 2021, while CO_2 emissions increased significantly due to LNG export terminals. However, CO_2 emissions decreased by 57% from 2020 to 2021, also due to LNG export terminals and flaring. Nitrous oxide emissions from transmission and storage increased from 1990 to 2021 but decreased in 2021.



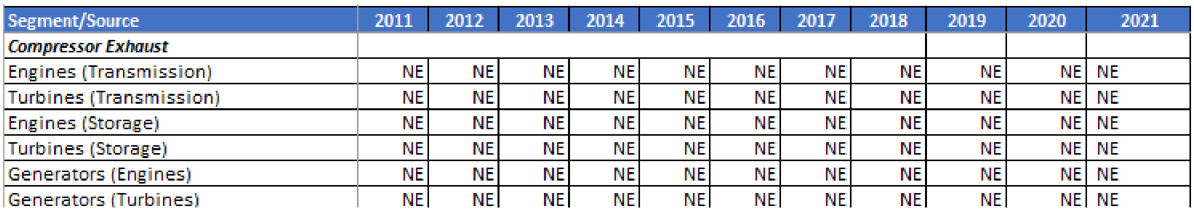
Segment/Source	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
TRANSMISSION AND STORAGE											
Net Emissions	**218.3**	**223.0**	**223.1**	**228.1**	**227.6**	**339.6**	**499.1**	**547.5**	**1,242.1**	**2,051.0**	**890.3**
Pipeline Leaks	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Compressor Stations (Transmission)											
Station Total Emissions	14.5	14.6	15.8	16.9	17.0	17.2	17.3	18.5	20.2	20.7	21.0
Station + Compressor Fugitive	2.8	3.0	3.2	3.5	3.5	3.5	3.6	3.8	4.2	4.3	4.3
Reciprocating Compressor	8.9	8.6	9.3	10.0	10.1	10.2	10.3	11.0	12.1	12.4	12.5
Centrifugal Compressor (wet seals)	1.4	1.5	1.6	1.7	1.7	1.6	1.5	1.6	1.7	1.7	1.6
Centrifugal Compressor (dry seals)	1.5	1.5	1.6	1.7	1.7	1.8	2.0	2.1	2.3	2.4	2.5
Compressor Stations (Storage)											
Station Total Emissions	4.0	3.9	3.9	3.9	3.8	3.8	3.8	3.7	3.8	3.8	3.8
Station + Compressor Fugitive	0.0	0.7	0.7	0.7	0.7	0.72	0.7	0.7	0.7	0.7	0.7
Reciprocating Compressor	0.0	3.1	3.1	3.1	3.1	3.0	3.0	3.0	3.0	3.0	3.0
Wells (Storage)	0.4	0.4	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
M&R (Trans. Co. Interconnect)	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
M&R (Farm Taps + Direct Sales)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5

Figure 2-11: Emissions from Compressor Stations



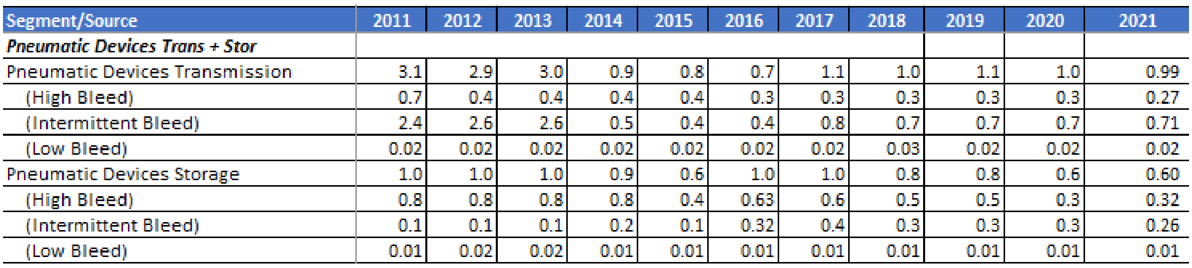
Segment/Source	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Normal Operation											
Dehydrator vents (Transmission)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Dehydrator vents (Storage)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Flaring (Transmission)	67.1	71.9	77.7	83.4	83.9	89.1	76.9	77.0	92.1	113.5	74.5
Flaring (Storage)	24.0	24.0	24.1	24.1	23.6	29.9	22.6	78.3	112.0	120.0	55.7

Figure 2-12: Emissions from Normal Operations of Transmission and Storage



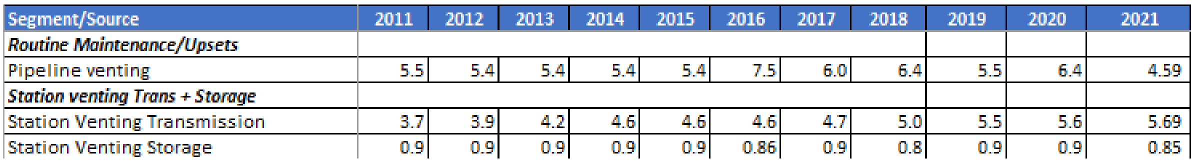
Segment/Source	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Compressor Exhaust											
Engines (Transmission)	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE
Turbines (Transmission)	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE
Engines (Storage)	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE
Turbines (Storage)	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE
Generators (Engines)	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE
Generators (Turbines)	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE

Figure 2-13: Emissions from Compressor Exhausts



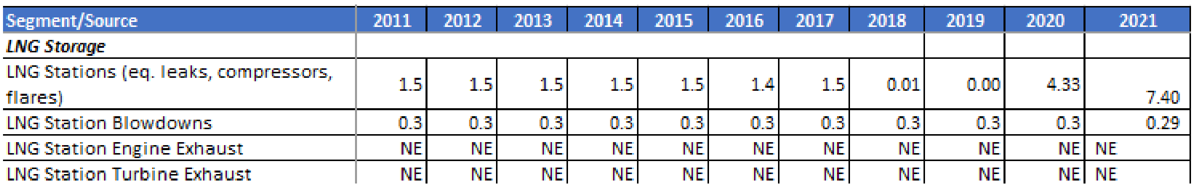
Segment/Source	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Pneumatic Devices Trans + Stor											
Pneumatic Devices Transmission	3.1	2.9	3.0	0.9	0.8	0.7	1.1	1.0	1.1	1.0	0.99
(High Bleed)	0.7	0.4	0.4	0.4	0.4	0.3	0.3	0.3	0.3	0.3	0.27
(Intermittent Bleed)	2.4	2.6	2.6	0.5	0.4	0.4	0.8	0.7	0.7	0.7	0.71
(Low Bleed)	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02	0.02
Pneumatic Devices Storage	1.0	1.0	1.0	0.9	0.6	1.0	1.0	0.8	0.8	0.6	0.60
(High Bleed)	0.8	0.8	0.8	0.8	0.4	0.63	0.6	0.5	0.5	0.3	0.32
(Intermittent Bleed)	0.1	0.1	0.1	0.2	0.1	0.32	0.4	0.3	0.3	0.3	0.26
(Low Bleed)	0.01	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01

Figure 2-14: Emissions from Pneumatic Devices of Trans + Storage



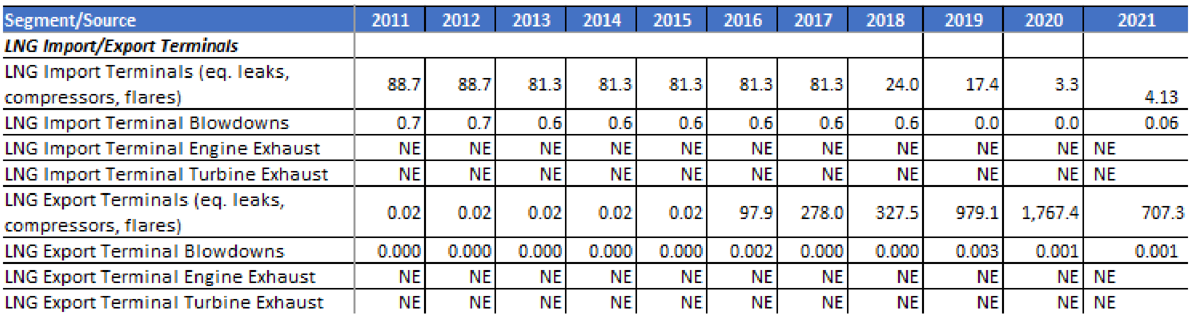
Segment/Source	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Routine Maintenance/Upsets											
Pipeline venting	5.5	5.4	5.4	5.4	5.4	7.5	6.0	6.4	5.5	6.4	4.59
Station venting Trans + Storage											
Station Venting Transmission	3.7	3.9	4.2	4.6	4.6	4.6	4.7	5.0	5.5	5.6	5.69
Station Venting Storage	0.9	0.9	0.9	0.9	0.9	0.86	0.9	0.8	0.9	0.9	0.85

Figure 2-15: Emissions from Routine Maintenance and Station Venting in Trans + Storage



Segment/Source	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
LNG Storage											
LNG Stations (eq. leaks, compressors, flares)	1.5	1.5	1.5	1.5	1.5	1.4	1.5	0.01	0.00	4.33	7.40
LNG Station Blowdowns	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.29
LNG Station Engine Exhaust	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE
LNG Station Turbine Exhaust	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE

Figure 2-16: Emissions from LNG Storage



Segment/Source	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
LNG Import/Export Terminals											
LNG Import Terminals (eq. leaks, compressors, flares)	88.7	88.7	81.3	81.3	81.3	81.3	81.3	24.0	17.4	3.3	4.13
LNG Import Terminal Blowdowns	0.7	0.7	0.6	0.6	0.6	0.6	0.6	0.6	0.0	0.0	0.06
LNG Import Terminal Engine Exhaust	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE
LNG Import Terminal Turbine Exhaust	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE
LNG Export Terminals (eq. leaks, compressors, flares)	0.02	0.02	0.02	0.02	0.02	97.9	278.0	327.5	979.1	1,767.4	707.3
LNG Export Terminal Blowdowns	0.000	0.000	0.000	0.000	0.000	0.002	0.000	0.000	0.003	0.001	0.001
LNG Export Terminal Engine Exhaust	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE
LNG Export Terminal Turbine Exhaust	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE

Figure 2-17: Emissions from LNG Import/Export Terminals

2.1.1.5 Distribution

This stage involves the transportation of high-pressure gas from the transmission system at "city gate" stations, where the pressure is reduced before distributing the gas through underground mains and service lines to individual end users. For example, in 2021, the distribution mains covered 1,337,012 miles, marking a significant increase of 392,855 miles since 1990.

The main sources of emissions in the distribution stage are leaks from pipelines and stations, producing mainly CH_4 and CO_2 emissions.

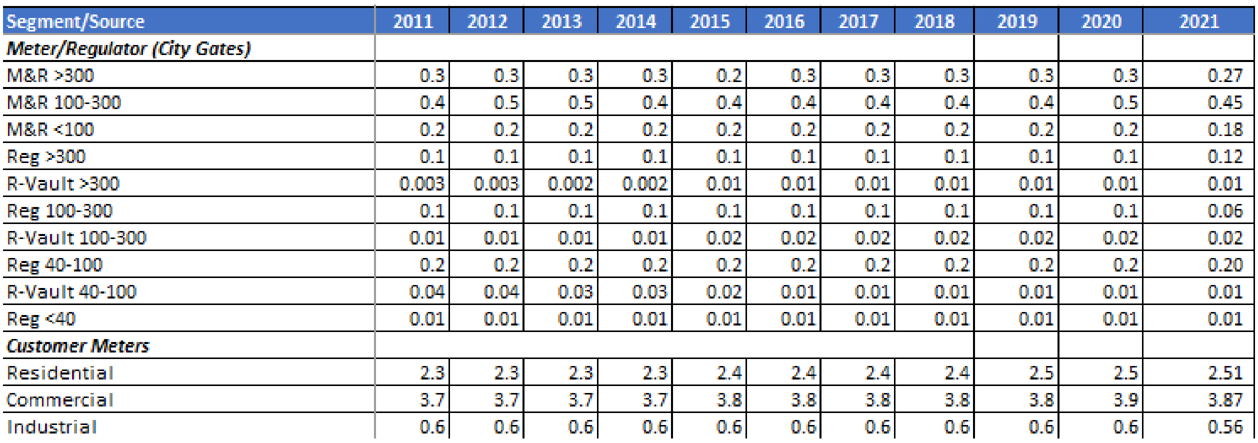
Over the years, emissions reduction has been achieved through the adoption of plastic piping, which has lower emissions compared to other materials, and station upgrades at metering and regulating (M&R) stations.

By 2021, the CH_4 emissions from the distribution system had decreased significantly, with a 70% reduction compared to 1990 levels. Similarly, the CO_2 emissions from the distribution system had also decreased by 70% compared to 1990 levels.

At this stage, post meter emissions are also included. The post-meter segment of natural gas systems includes leak emissions from residential and commercial appliances, industrial facilities and power plants, and natural gas-fueled vehicles. Most of the CH_4 emissions stem from residential appliances and industrial facilities.

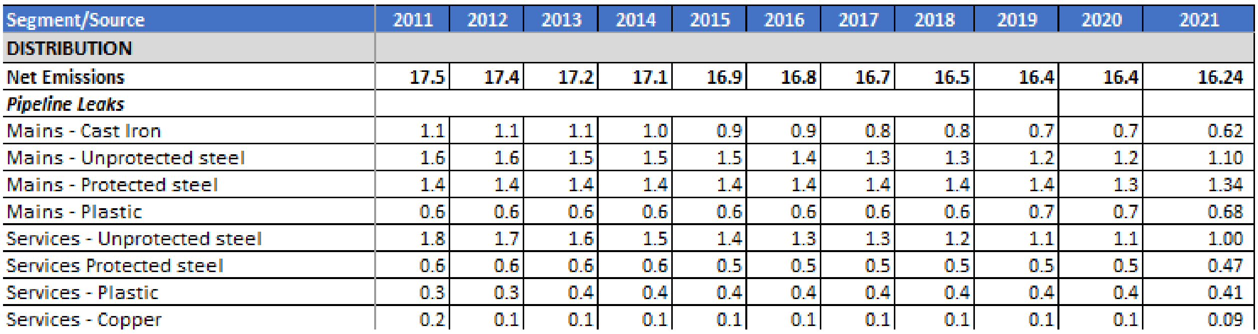
In 2021, post-meter CH_4 emissions accounted for approximately 7% of total emissions from natural gas systems. Over the period from 1990 to 2021, post-meter CH_4 emissions increased by 60%, mainly due to the growing number of residential houses using natural gas and increased natural gas consumption at industrial facilities and power plants.

As for carbon dioxide (CO_2) emissions, post-meter sources account for less than 0.01 percent of total CO_2 emissions from natural gas systems.



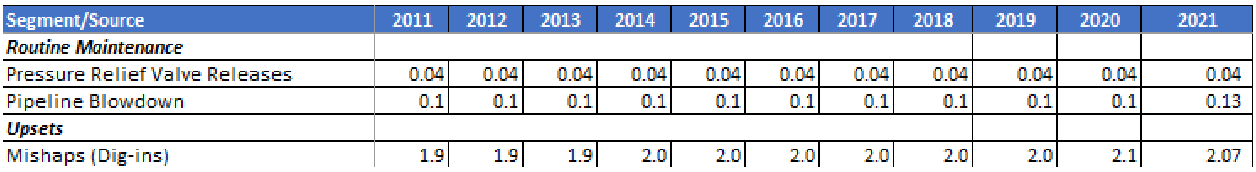
Segment/Source	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Meter/Regulator (City Gates)											
M&R >300	0.3	0.3	0.3	0.3	0.2	0.3	0.3	0.3	0.3	0.3	0.27
M&R 100-300	0.4	0.5	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.45
M&R <100	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.18
Reg >300	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.12
R-Vault >300	0.003	0.003	0.002	0.002	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Reg 100-300	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.06
R-Vault 100-300	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Reg 40-100	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.20
R-Vault 40-100	0.04	0.04	0.03	0.03	0.02	0.01	0.01	0.01	0.01	0.01	0.01
Reg <40	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Customer Meters											
Residential	2.3	2.3	2.3	2.3	2.4	2.4	2.4	2.4	2.5	2.5	2.51
Commercial	3.7	3.7	3.7	3.7	3.8	3.8	3.8	3.8	3.8	3.9	3.87
Industrial	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.56

Figure 2-18: Emissions from Meters in City Distribution



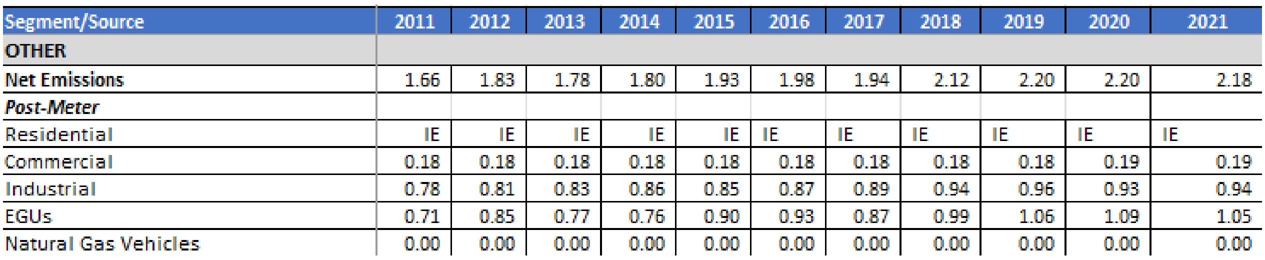
Segment/Source	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
DISTRIBUTION											
Net Emissions	**17.5**	**17.4**	**17.2**	**17.1**	**16.9**	**16.8**	**16.7**	**16.5**	**16.4**	**16.4**	**16.24**
Pipeline Leaks											
Mains - Cast Iron	1.1	1.1	1.1	1.0	0.9	0.9	0.8	0.8	0.7	0.7	0.62
Mains - Unprotected steel	1.6	1.6	1.5	1.5	1.5	1.4	1.3	1.3	1.2	1.2	1.10
Mains - Protected steel	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.3	1.34
Mains - Plastic	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.7	0.7	0.68
Services - Unprotected steel	1.8	1.7	1.6	1.5	1.4	1.3	1.3	1.2	1.1	1.1	1.00
Services Protected steel	0.6	0.6	0.6	0.6	0.5	0.5	0.5	0.5	0.5	0.5	0.47
Services - Plastic	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.41
Services - Copper	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.09

Figure 2-19: Emissions from Distribution Pipeline Leaks



Segment/Source	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Routine Maintenance											
Pressure Relief Valve Releases	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Pipeline Blowdown	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.13
Upsets											
Mishaps (Dig-ins)	1.9	1.9	1.9	2.0	2.0	2.0	2.0	2.0	2.0	2.1	2.07

Figure 2-20: Emissions from Routine Maintenance + Upsets in Distribution



Segment/Source	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
OTHER											
Net Emissions	1.66	1.83	1.78	1.80	1.93	1.98	1.94	2.12	2.20	2.20	2.18
Post-Meter											
Residential	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE
Commercial	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.19	0.19
Industrial	0.78	0.81	0.83	0.86	0.85	0.87	0.89	0.94	0.96	0.93	0.94
EGUs	0.71	0.85	0.77	0.76	0.90	0.93	0.87	0.99	1.06	1.09	1.05
Natural Gas Vehicles	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Figure 2-21: Other Emissions in Distribution

2.1.2 GHG Emissions (CH4, CO2, N2O) categorized in Basins.

The **"Inventory of U.S Greenhouse Gas Emissions and Sinks"** [42] contains an update that incorporates additional basin-level data. The purpose of this update is to improve the accuracy of emission estimates for various sources in the onshore production segment. It also aims to capture variations in emissions due to factors like formation types, technologies, regulations, and voluntary initiatives. This would allow for better comparisons with atmospheric observation studies and enable state-level inventories to reflect local differences in emissions rates.

The **CH_4** emissions data of this section have only been collected for selected **Natural Gas Systems** that are presented below and have been categorized by segment:

1. **Well Pad Equipment Leaks**
    - 1.1. Separators
    - 1.2. Heaters
    - 1.3. Dehydrators
    - 1.4. Meters Piping
    - 1.5. Compressors
2. **Chemical Injection Pumps**
3. **Pneumatic Controllers**
    - 3.1. High Bleed
    - 3.2. Low Bleed
    - 3.3. Intermittent Bleed
4. **Tanks**
    - 4.1. Large Tanks w/VRU
    - 4.2. Large Tanks w/o Control
    - 4.3. Small Tanks w/o Flares
    - 4.4. Malfunctioning Separator Dump Valves
    - 4.5. Large Tanks w/Flares
    - 4.6. Small Tanks w/Flares
5. **Liquids Unloading**
    - 5.1. Liquids Unloading with Plunger Lifts
    - 5.2. Liquids Unloading without Plunger Lifts

Similarly, the **CO_2** emissions have been collected for the following systems and segments of production:

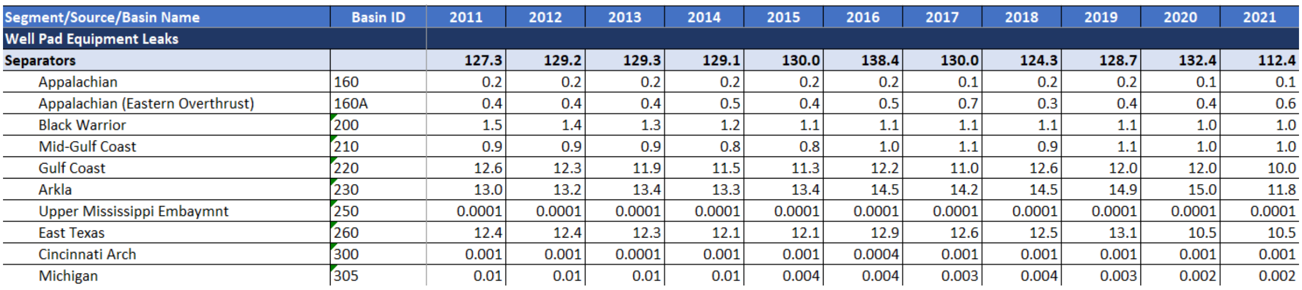
1. **Tanks**
    - 1.1. Large Tanks w/VRU
    - 1.2. Large Tanks w/o Control
    - 1.3. Small Tanks w/o Flares
    - 1.4. Malfunctioning Separator Dump Valves
    - 1.5. Large Tanks w/Flares
    - 1.6. Small Tanks w/Flares

2. **Well Clean-ups**
    2.1. Liquids Unloading with Plunger Lifts
    2.2. Liquids Unloading without Plunger Lifts

The emissions data of the Natural Gas Systems have been collected for 96 different US Basins such us:

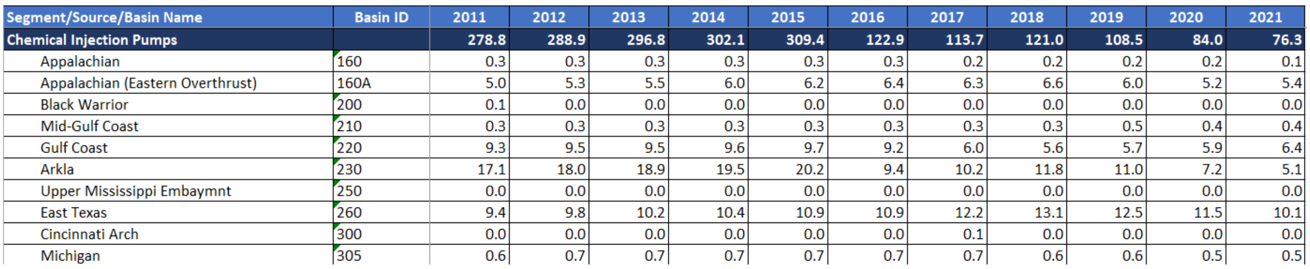
- New England Province
- Atlantic Coast
- Florida Platform
- Appalachian
- Mid-Gulf Coast
- Gulf Coast
- East Texas
- Cincinnati Arch
- Michigan
- Illinois

Examples of this update's dataset (obtained from "2023_ghgi_natural_gas_systems_annex36_tables" excel) are provided in the following figures:



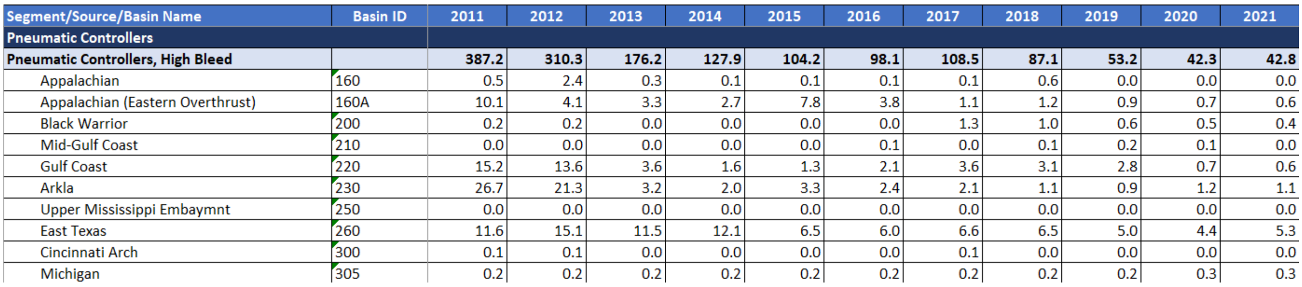
Segment/Source/Basin Name	Basin ID	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Well Pad Equipment Leaks												
Separators		**127.3**	**129.2**	**129.3**	**129.1**	**130.0**	**138.4**	**130.0**	**124.3**	**128.7**	**132.4**	**112.4**
Appalachian	160	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.2	0.2	0.1	0.1
Appalachian (Eastern Overthrust)	160A	0.4	0.4	0.4	0.5	0.4	0.5	0.7	0.3	0.4	0.4	0.6
Black Warrior	200	1.5	1.4	1.3	1.2	1.1	1.1	1.1	1.1	1.1	1.0	1.0
Mid-Gulf Coast	210	0.9	0.9	0.9	0.8	0.8	1.0	1.1	0.9	1.1	1.0	1.0
Gulf Coast	220	12.6	12.3	11.9	11.5	11.3	12.2	11.0	12.6	12.0	12.0	10.0
Arkla	230	13.0	13.2	13.4	13.3	13.4	14.5	14.2	14.5	14.9	15.0	11.8
Upper Mississippi Embaymnt	250	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
East Texas	260	12.4	12.4	12.3	12.1	12.1	12.9	12.6	12.5	13.1	10.5	10.5
Cincinnati Arch	300	0.001	0.001	0.0001	0.001	0.001	0.0004	0.001	0.001	0.001	0.001	0.001
Michigan	305	0.01	0.01	0.01	0.01	0.004	0.004	0.003	0.004	0.003	0.002	0.002

Figure 2-22: Basin-Level Emissions of Separators



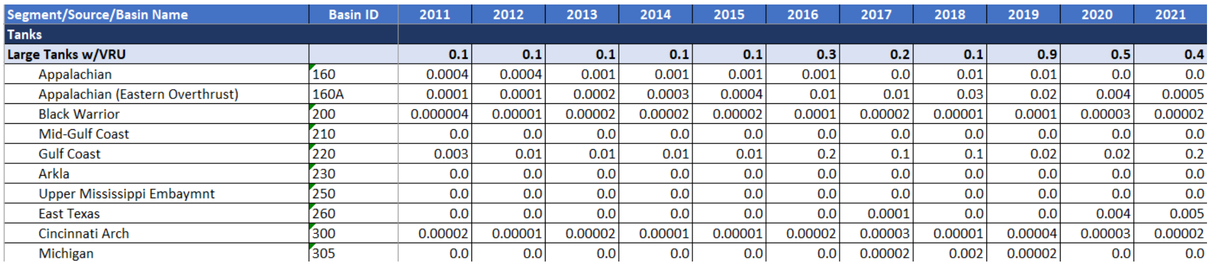
Segment/Source/Basin Name	Basin ID	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Chemical Injection Pumps		**278.8**	**288.9**	**296.8**	**302.1**	**309.4**	**122.9**	**113.7**	**121.0**	**108.5**	**84.0**	**76.3**
Appalachian	160	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.1
Appalachian (Eastern Overthrust)	160A	5.0	5.3	5.5	6.0	6.2	6.4	6.3	6.6	6.0	5.2	5.4
Black Warrior	200	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mid-Gulf Coast	210	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.5	0.4	0.4
Gulf Coast	220	9.3	9.5	9.5	9.6	9.7	9.2	6.0	5.6	5.7	5.9	6.4
Arkla	230	17.1	18.0	18.9	19.5	20.2	9.4	10.2	11.8	11.0	7.2	5.1
Upper Mississippi Embaymnt	250	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
East Texas	260	9.4	9.8	10.2	10.4	10.9	10.9	12.2	13.1	12.5	11.5	10.1
Cincinnati Arch	300	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0
Michigan	305	0.6	0.7	0.7	0.7	0.7	0.7	0.7	0.6	0.6	0.5	0.5

Figure 2-23: Basin-Level Emissions of Chemical Injection Pumps



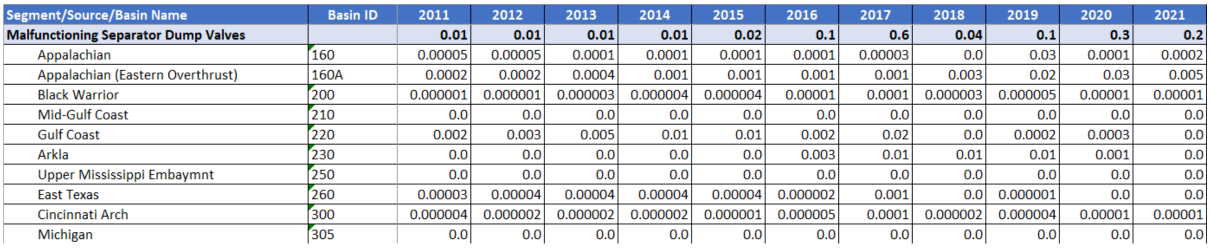
Segment/Source/Basin Name	Basin ID	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Pneumatic Controllers												
Pneumatic Controllers, High Bleed		**387.2**	**310.3**	**176.2**	**127.9**	**104.2**	**98.1**	**108.5**	**87.1**	**53.2**	**42.3**	**42.8**
Appalachian	160	0.5	2.4	0.3	0.1	0.1	0.1	0.1	0.6	0.0	0.0	0.0
Appalachian (Eastern Overthrust)	160A	10.1	4.1	3.3	2.7	7.8	3.8	1.1	1.2	0.9	0.7	0.6
Black Warrior	200	0.2	0.2	0.0	0.0	0.0	0.0	1.3	1.0	0.6	0.5	0.4
Mid-Gulf Coast	210	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.2	0.1	0.0
Gulf Coast	220	15.2	13.6	3.6	1.6	1.3	2.1	3.6	3.1	2.8	0.7	0.6
Arkla	230	26.7	21.3	3.2	2.0	3.3	2.4	2.1	1.1	0.9	1.2	1.1
Upper Mississippi Embaymnt	250	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
East Texas	260	11.6	15.1	11.5	12.1	6.5	6.0	6.6	6.5	5.0	4.4	5.3
Cincinnati Arch	300	0.1	0.1	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0
Michigan	305	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3

Figure 2-24: Basin-Level emissions of Pneumatic Controllers



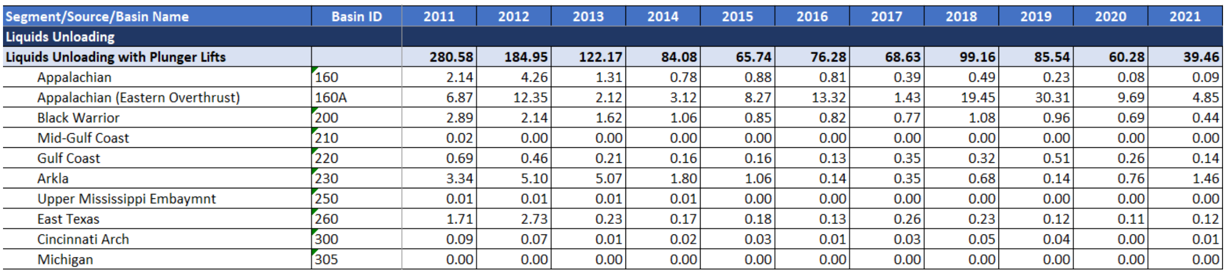
Segment/Source/Basin Name	Basin ID	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Tanks												
Large Tanks w/VRU		**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.3**	**0.2**	**0.1**	**0.9**	**0.5**	**0.4**
Appalachian	160	0.0004	0.0004	0.001	0.001	0.001	0.001	0.0	0.01	0.01	0.0	0.0
Appalachian (Eastern Overthrust)	160A	0.0001	0.0001	0.0002	0.0003	0.0004	0.01	0.01	0.03	0.02	0.004	0.0005
Black Warrior	200	0.000004	0.00001	0.00002	0.00002	0.00002	0.0001	0.00002	0.00001	0.0001	0.00003	0.00002
Mid-Gulf Coast	210	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Gulf Coast	220	0.003	0.01	0.01	0.01	0.01	0.2	0.1	0.1	0.02	0.02	0.2
Arkla	230	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Upper Mississippi Embaymnt	250	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
East Texas	260	0.0	0.0	0.0	0.0	0.0	0.0	0.0001	0.0	0.0	0.004	0.005
Cincinnati Arch	300	0.00002	0.00001	0.00002	0.00001	0.00001	0.00002	0.00003	0.00001	0.00004	0.00003	0.00002
Michigan	305	0.0	0.0	0.0	0.0	0.0	0.0	0.00002	0.002	0.00002	0.0	0.0

Figure 2-25: Basin-Level Emissions of Large Tanks w/VRU



Segment/Source/Basin Name	Basin ID	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Malfunctioning Separator Dump Valves		**0.01**	**0.01**	**0.01**	**0.01**	**0.02**	**0.1**	**0.6**	**0.04**	**0.1**	**0.3**	**0.2**
Appalachian	160	0.00005	0.00005	0.0001	0.0001	0.0001	0.0001	0.00003	0.0	0.03	0.0001	0.0002
Appalachian (Eastern Overthrust)	160A	0.0002	0.0002	0.0004	0.001	0.001	0.001	0.001	0.003	0.02	0.03	0.005
Black Warrior	200	0.000001	0.000001	0.000003	0.000004	0.000004	0.00001	0.0001	0.000003	0.000005	0.00001	0.00001
Mid-Gulf Coast	210	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Gulf Coast	220	0.002	0.003	0.005	0.01	0.01	0.002	0.02	0.0	0.0002	0.0003	0.0
Arkla	230	0.0	0.0	0.0	0.0	0.0	0.003	0.01	0.01	0.01	0.001	0.0
Upper Mississippi Embaymnt	250	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
East Texas	260	0.00003	0.00004	0.00004	0.00004	0.00004	0.000002	0.001	0.0	0.000001	0.0	0.0
Cincinnati Arch	300	0.000004	0.000002	0.000002	0.000002	0.000001	0.000005	0.0001	0.000002	0.000004	0.00001	0.00001
Michigan	305	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Figure 2-26: Basin-Level Emissions of Malfunctioning Separator Dump Valves



Segment/Source/Basin Name	Basin ID	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Liquids Unloading												
Liquids Unloading with Plunger Lifts		**280.58**	**184.95**	**122.17**	**84.08**	**65.74**	**76.28**	**68.63**	**99.16**	**85.54**	**60.28**	**39.46**
Appalachian	160	2.14	4.26	1.31	0.78	0.88	0.81	0.39	0.49	0.23	0.08	0.09
Appalachian (Eastern Overthrust)	160A	6.87	12.35	2.12	3.12	8.27	13.32	1.43	19.45	30.31	9.69	4.85
Black Warrior	200	2.89	2.14	1.62	1.06	0.85	0.82	0.77	1.08	0.96	0.69	0.44
Mid-Gulf Coast	210	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Gulf Coast	220	0.69	0.46	0.21	0.16	0.16	0.13	0.35	0.32	0.51	0.26	0.14
Arkla	230	3.34	5.10	5.07	1.80	1.06	0.14	0.35	0.68	0.14	0.76	1.46
Upper Mississippi Embaymnt	250	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
East Texas	260	1.71	2.73	0.23	0.17	0.18	0.13	0.26	0.23	0.12	0.11	0.12
Cincinnati Arch	300	0.09	0.07	0.01	0.02	0.03	0.01	0.03	0.05	0.04	0.00	0.01
Michigan	305	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Figure 2-27: Basin-Level Emissions of Liquids Unloading with Plunger Lifts

This in-depth update that provides specific emissions per US basin constitutes the dataset of this thesis's Blockchain Application. It provides a very distinct categorization of emissions that facilitates the application of Blockchain Technology, as it will be explained in the following chapters.

2.2 The multi-tier supply chain system

Prior to implementing blockchain, it is crucial to divide the supply chain network into tiers, which will subsequently align with blocks and blockchains.

As indicated in reference [43], this division of the Natural Gas supply chain network should resemble the division seen in a production line, such as that of a flashlight.

2.2.1 The Torchlight Architecture

To understand how emissions recording is structured within a multi-tier supply chain system, a straightforward example will be illustrated: a production line flashlight.

A torchlight, which is a portable hand-held electric lamp powered by batteries consists of 18 [43] different components. The most common of them are [44]:

- **Light bulb**: The light-emitting component that produces the light.
- **Two electric cells (battery)**: The power source that provides electricity to the flashlight.
- **Metallic spring and wire (mostly copper)**: The component that serves as a conductor to transmit electric current from the batteries to power the light source.
- **Switch**: The mechanism that turns the flashlight on and off.

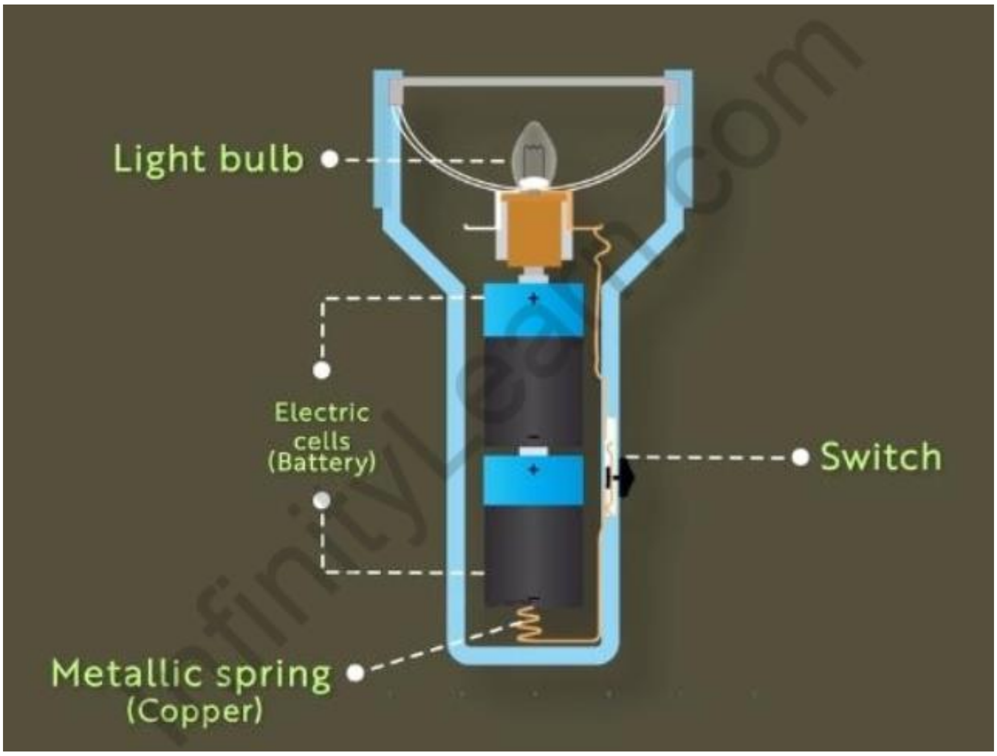


Figure 2-28: Light Bulb Components

The torchlight also consists of other components such us:

- **Casing**
- **Battery Compartment**
- **Lens or Cover**
- **Circuit Board**
- **Driver Circuit**
- **Heat Sink**
- **O-rings or Gaskets**
- **Tail Cap**
- **Head or Bezel**
- **Clip or Lanyard Ring**
- **Battery Springs or Contacts**
- **Modes Selector**
- **Waterproofing Seals**
- **Knurling or Grip Patterns**

These components originate from various manufacturers, and each of these manufacturers might rely on another group of suppliers to provide them with subcomponents. This interconnected structure forms a multi-tiered supply chain. This multi-tiered supply chain is described by Figure 2-29 [43]:

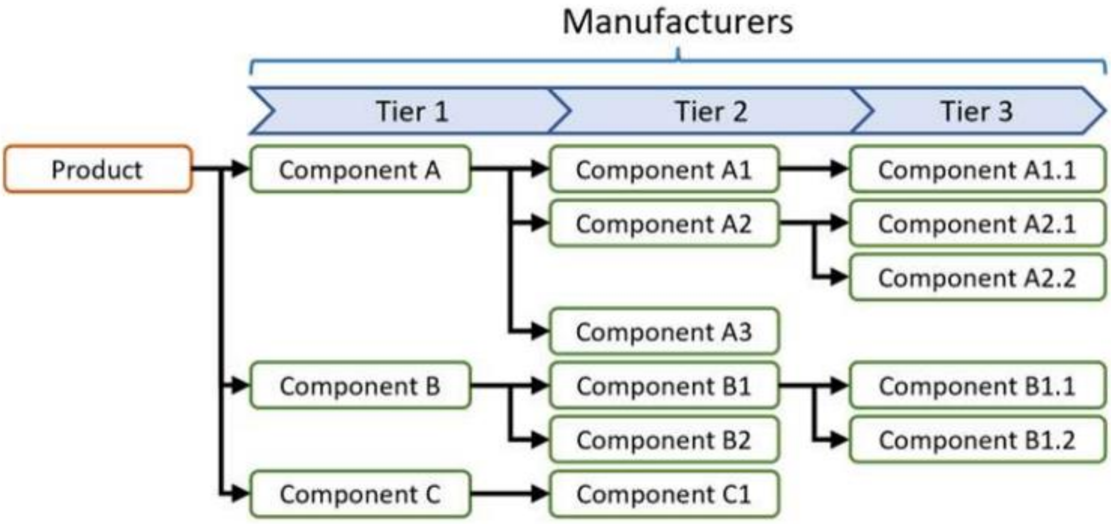


Figure 2-29: Multi-Tier Supply Chain Example

To determine the total emissions from the production of a torchlight, or a batch of torchlights, it is essential to monitor the emissions associated with the manufacturing of each individual component (tiers) used in assembling the product. This model exhibits similarities to the well-known **Russian Doll Model**:

Russian Doll Model:

Figure 2-30: Russian Doll

The model is based on the idea that a product consists of sub-assemblies with components that have sub-components supplied by different manufacturers. The emissions of a product are calculated by accounting the emissions associated with the fabrication of components by the manufacturer (**material emissions**) and the emissions of components that are fabricated by a third party (**device emissions**). In other words, the emissions of a product are influenced by the emission of its components, which are in turn influenced by the emission of their sub-components, and so on. Therefore, to accurately capture the cradle-to-gate emissions of a product, there is a need for a system that can effectively store and propagate the product's emissions for access by relevant parties down the supply chain.

To visualize this idea, the Figure 2-31 is provided:

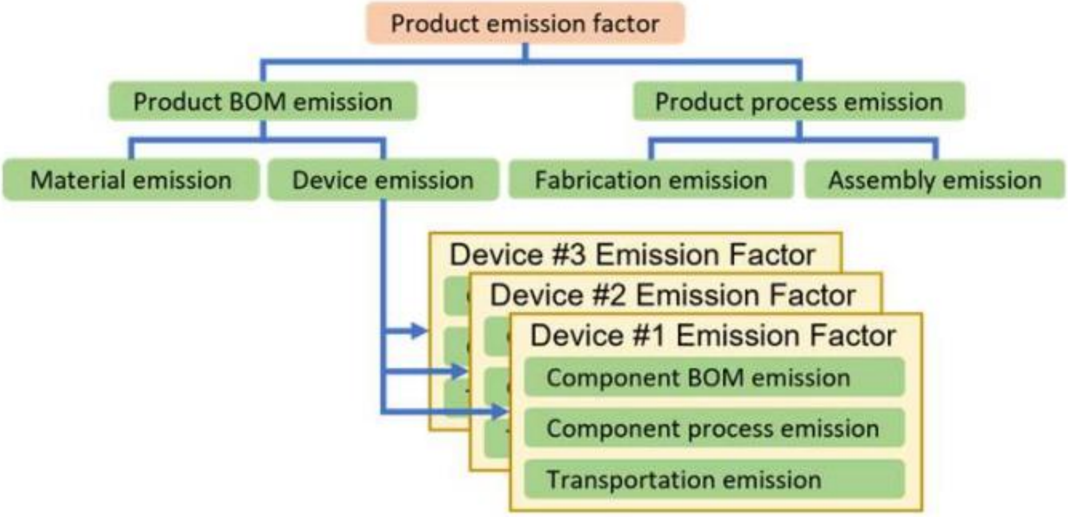


Figure 2-31: Product Emissions Tree

The Torchlight represents the final product. As mentioned before, the torchlight consists of 18 components. Some of these components are manufactured in-house (material emissions) and some developed by a third-party (device emissions).

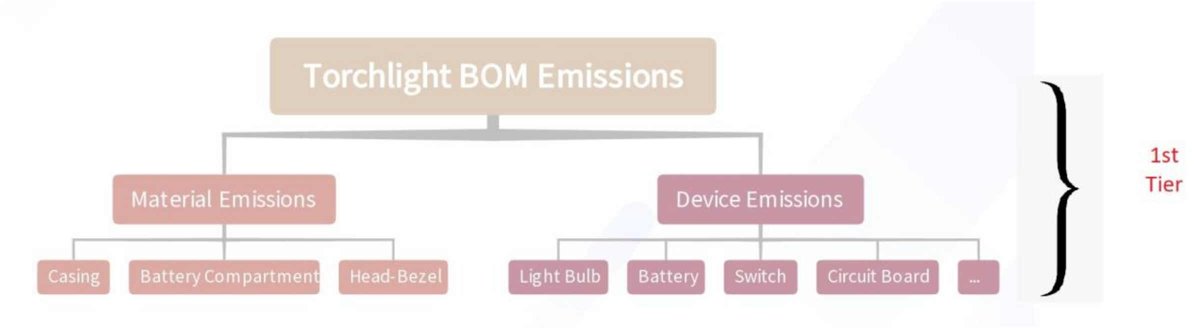


Figure 2-32: Torchlight BOM 1st Tier

In order expand this analysis to the next tier, the elements of the specific devices need to be examined. Therefore, the different components of the Light Bulb, a vital component of the Torchlight, have been studied. The Light Bulb consists of many different components [45] such as the:

- **Globe**: the outer glass shell of the light bulb.
- **Filament**: the coil that produces light.
- **Wires**: ensure the steady flow of electricity through the components of the light bulb.
- **Stem**: It is placed in the centre of the light bulb and supports the filament in its place.
- **Invisible Gases**: inert gases usually formed of argon and/or nitrogen. They prevent the filament inside the bulb from burning out.
- **Base of the light bulb**

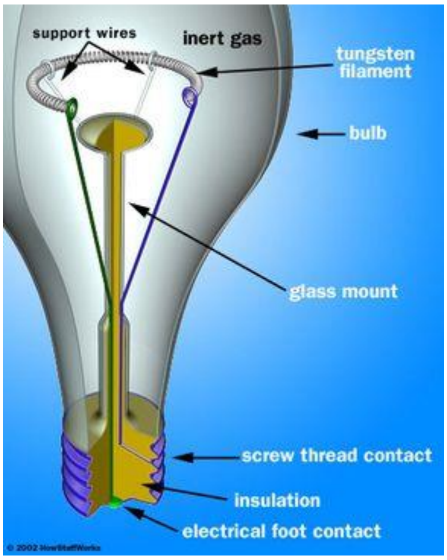


Figure 2-33: Light Bulb Components

At this stage the emissions that need to be accounted for this device are:

- **Emissions from the Components in the BOM**: For example, the base of the light bulb consists of other components, whose emissions should also be included.
- **Components Process Emissions**: Emissions caused in the process of manufacturing and assembling these components.
- **Transportation Emissions**: Emissions that were caused by transportation of the component from the third-party manufacturer to the Torchlight Manufacturer.

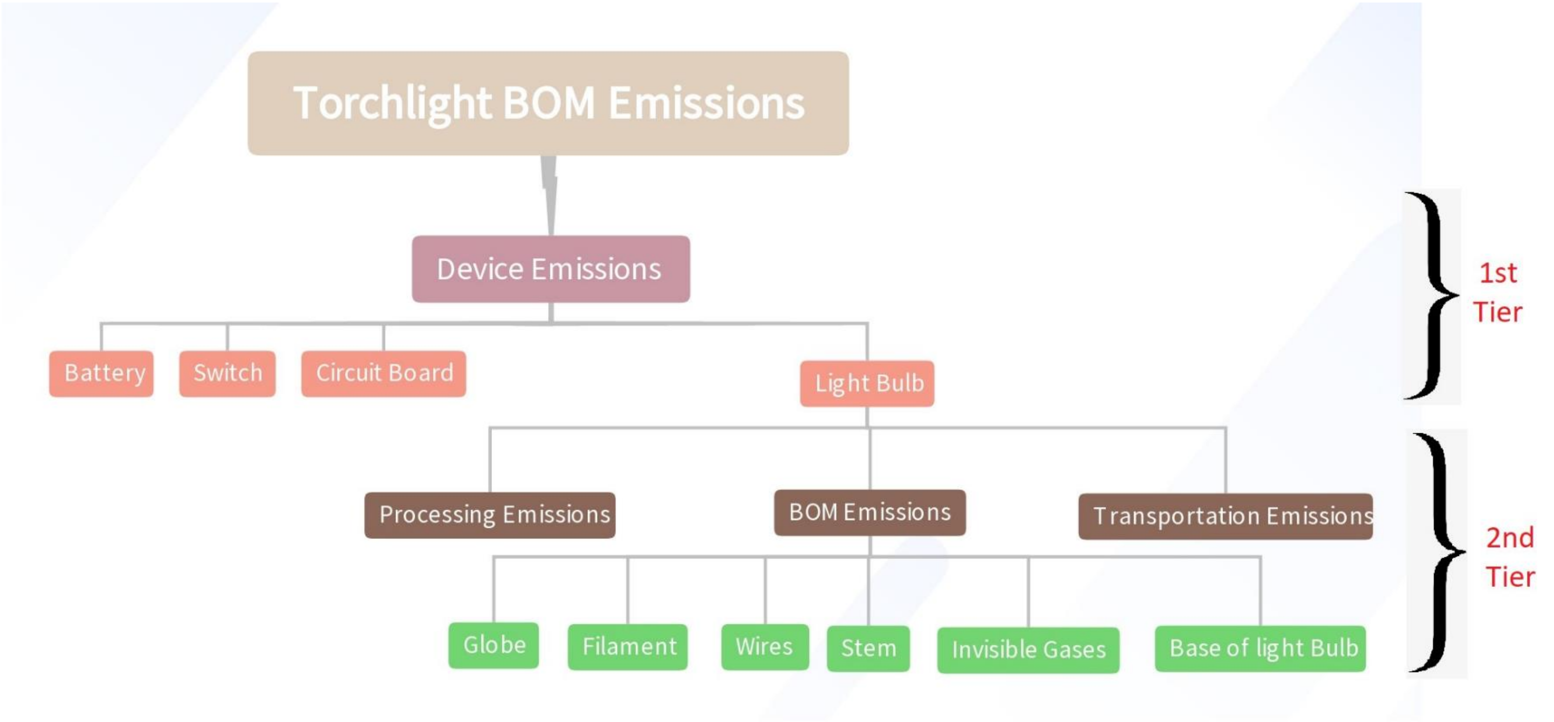


Figure 2-34: Torchlight BOM 2nd Tier

The same process would be carried out for all the subcomponents of the Light Bulb till the root tier is reached (raw materials). The number of tiers depends on the complexity of the final product.

The total emissions from the production of a product arise from the summation of the individual emissions from their subcomponents and the processes involved in their manufacturing.

2.2.2 Implementation of the Torchlight in the Blockchain

Before explaining the architecture, it is important to note that for a Blockchain System to work there is the need of cooperation from all parties, meaning the manufacturers of the product and its subcomponents.

Manufacturers might exhibit reluctance towards adopting the suggested system due to apprehensions about revealing their operational activities. This hesitancy arises from the fact that the system mandates all supply chain participants to provide real-time data of their operations to the blockchain. This increased level of transparency and full disclosure of data from the factories, especially when not subject to regulatory compliance, imposes restrictions in the flexibility of operations of the manufacturers, that will probably cause complaints from their side.

Since approval to participate in the system has been given from all sides, a permissioned or private blockchain system will be setup. In contrast to a public blockchain open to all, only manufacturers authorized by the network owner can enter and contribute to the blockchain. Therefore, the manufacturer of the final product would need to whitelist all the manufacturers involved in the production of its subcomponents. This might be challenging since manufacturers usually don't engage with lower-tier manufacturers with whom they lack direct business interactions.

Now that it’s evident that all entities involved in the production of the product and its subcomponents need to provide real-time data of their operations, the architecture of the proposed blockchain system will be further examined.

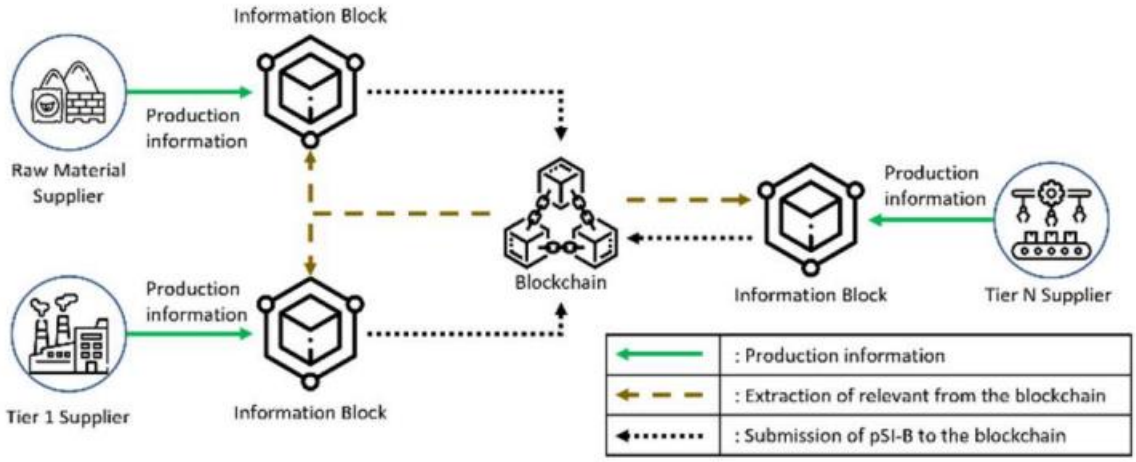


Figure 2-35: Proposed Blockchain System Architecture [43]

The figure 2-35 demonstrates:

- The recording of operational data from suppliers to blocks.
- The effect that information stored in the blockchain has on different blocks.
- The submission of new blocks in the blockchain.

According to reference [43], the blocks, the foundation of the blockchain system, store data that concern the emissions from products and processes utilizing emission factors.

An emissions factor [15] is a value that correlates the amount of a pollutant released into the air with an associated activity causing the release. These factors are often expressed as pollutant weight divided by a unit measure like weight, volume, distance, or time of the activity (e.g., kilograms of particulate per megagram of coal burned).

The general equation for Emissions calculation is the following:

$$E = A * EF * \frac{1 - ER}{100}$$

Where:

- E: Emissions
- A: Activity Rate
- EF: Emissions Factor
- ER: Overall emission reduction efficiency, %

According to reference [43], each product or process (block) when submitted into the system must meet some functional requirements (prerequisites):

1. Each product submitted needs to have its own **unique ID**, that distinguishes from other products and makes it traceable.
2. Each process needs to have its own **unique ID** as well, that distinguishes from other products and makes it traceable.
3. Each process should be **linked** to the product it represents and stored in order.
4. The information of a product can only be accessed by those who are aware of its stock-keeping unit (SKU).
5. Various access levels are assigned to different types of supply chain participants.
6. The structure of the blocks representing products and processes should always include the following properties:
    a. Structure of a product:

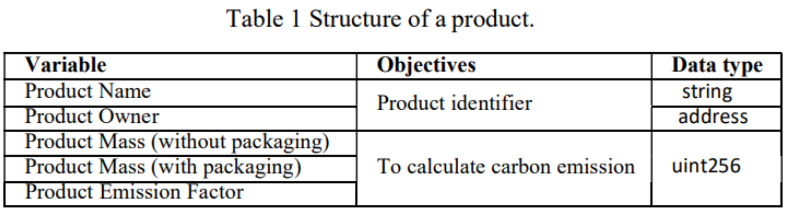


Table 1 Structure of a product.

Variable	Objectives	Data type
Product Name	Product identifier	string
Product Owner		address
Product Mass (without packaging)	To calculate carbon emission	uint256
Product Mass (with packaging)		
Product Emission Factor		

Figure 2-36: Structure of a Product Block

Product's Unique ID: The ID that distinguishes the product from other products submitted in the blockchain. The simplest form of a unique ID is an index (uint256) that starts from 0 and continues to infinity as products (blocks) are added in the blockchain.

b. Structure of a process:

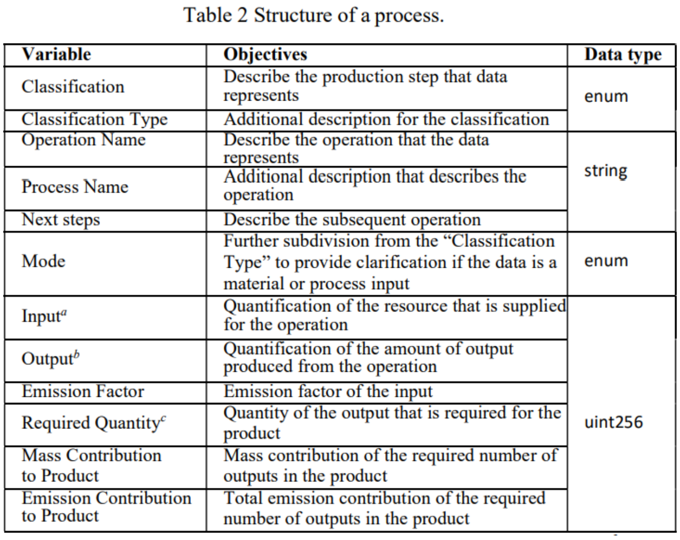


Table 2 Structure of a process.

Variable	Objectives	Data type
Classification	Describe the production step that data represents	enum
Classification Type	Additional description for the classification	
Operation Name	Describe the operation that the data represents	string
Process Name	Additional description that describes the operation	
Next steps	Describe the subsequent operation	
Mode	Further subdivision from the "Classification Type" to provide clarification if the data is a material or process input	enum
Input[a]	Quantification of the resource that is supplied for the operation	uint256
Output[b]	Quantification of the amount of output produced from the operation	
Emission Factor	Emission factor of the input	
Required Quantity[c]	Quantity of the output that is required for the product	
Mass Contribution to Product	Mass contribution of the required number of outputs in the product	
Emission Contribution to Product	Total emission contribution of the required number of outputs in the product	

Figure 2-37: Structure of a process block

In addition to the above properties, two more should be added:

1. **Process's unique ID:** The identifier that marks that process as unique from every other process.
2. **Product's unique ID:** The ID of the product that the process is linked to.

Both products and processes are represented by a unique code that proves their uniqueness. Also, each sub-process for the manufacturing of a product carries the product ID so that their direct correlation is evident. This enables the user to easily request data concerning a product's emissions or its sub-process's emissions.

2.2.3 The Natural Gas Supply Chain System Architecture

The purpose of this section is to present the architecture of the Natural Gas Supply Chain, as proposed in Section 2.1.1, as a multi-tier system. The creation of such an architecture requires some concessions to be made:

1) Division of Natural Gas Stream into batches:

In a normal production facility like a factory, the batch production involves the simultaneous production of a set of identical products as opposed to creating them one by one. The manufacturer determines the size of each batch and the frequency at which these batches are produced. [46] Each batch progresses through the distinct phases of the manufacturing process collectively. This implies that the commencement of a new batch in a particular phase is contingent upon the completion of the prior batch in that same phase.

In the case of Natural Gas, dividing natural gas output into batches involves grouping the gas production into distinct quantities that are processed, transported, or utilized together. To do so, some of the following criteria of batch division need to be considered:

- **Batch Characteristics**: The division of natural gas into batches requires the creation of batches with similar characteristics. Such characteristics are volume, composition, quality, source, destination, processing requirements, or time intervals (daily, weekly, etc.).
- **Batch Quantity**: There is the need to quantify the batches of natural gas. For instance, batches of a specific volume, such as 10,000 cubic meters, or based on a time interval, like a daily batch. For the purpose of this thesis, **each batch** has:
    - **Volume**: 202 cubic meters. This is the volume required to produce 1MWh of electricity. This assumption is based on [47].
    - **The same extraction point**: To achieve maximum uniformity in the characteristics of the Natural gas, as well the same processing requirements, each batch should originate from the same extraction point.

Alongside the extraction, processing, and distribution of natural gas batches, emissions from leaks, machinery usage etc. will be collected in the blockchain.

2) Definition of the Final Product

In an attempt to associate the multi-tier Natural Gas supply chain system to the Torchlight supply chain presented in section 2.2.1, the need to define the final product arises. In the case of natural gas, the final product is the **main-stream** (the main network of pipelines) in which all the sub-streams (batches) end up.

To grasp this concept, the real-life scenario of the Nord-stream is explained. Nord Stream refers to two natural gas pipelines that run beneath the Baltic Sea, connecting Russia to Germany. The full name of these pipelines is Nord Stream 1 and Nord Stream 2.

- **Nord Stream 1**: A set of twin pipelines that started operation in 2011. It runs from Vyborg in Russia to Lubmin in Germany, covering a distance of approximately 1,224 kilometers (760 miles). These pipelines have the capacity to transport a significant amount of natural gas.
- **Nord Stream 2:** An extension of the original Nord Stream project. It involves the construction of two additional pipelines alongside the existing Nord Stream 1 pipelines.

Figure 2-38: The Nord-Stream Route

Nord Stream's twin pipeline system has the capacity to transport up to **55 billion cubic metres** of natural gas from Russia to Europe through the Baltic Sea [48].

According to [49], the Nord Stream Gas pipeline is supplied by several fields (batches) in Russia such as:

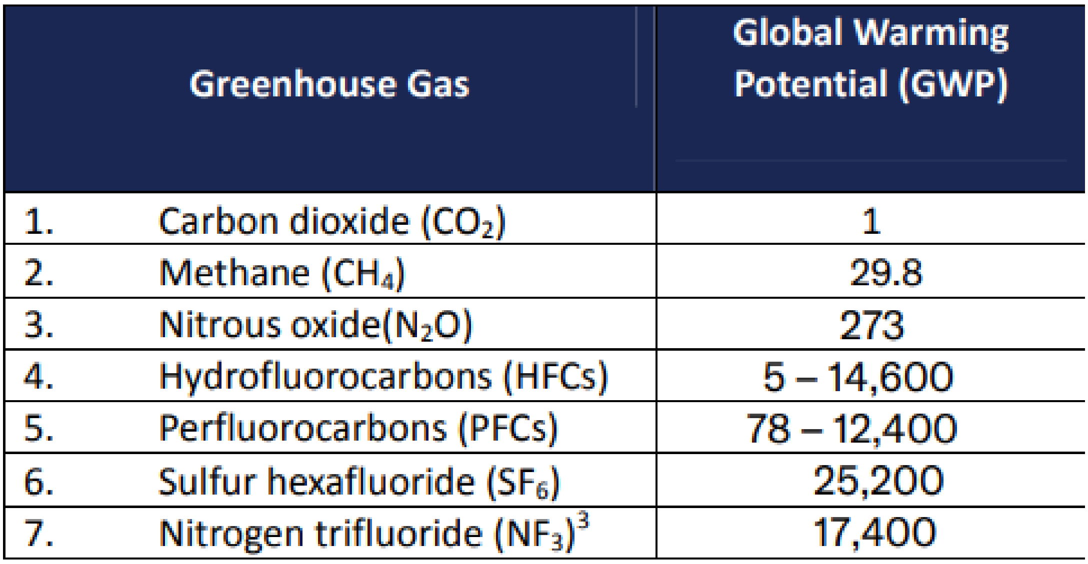
- Yuzhno-Russkoye (the main source), located in Krasnoselkupsky District.
- Several different fields in Yamal Peninsula, Ob-Taz bay.

3) Units of Measurement

As referenced in section 3.1.1 the most common type of emissions for natural gas systems are CH_4, CO_2 and N_2O measured in kilotons (kt). As the chemical composition of these gases varies, so does the pollution rate per kilogram (kg). Therefore, the term CO_2 equivalent (CO_2e) has been adopted.

This CO_2e term is used to describe various greenhouse gases using a common measure. For any greenhouse gas type and quantity, CO_2e signifies the equivalent global warming impact in terms of carbon dioxide [50].

To express a quantity of greenhouse gas as CO_2e, the amount of the gas (kg) is multiplied by its Global Warming Potential (GWP) according to figure 3-39 [50]:



Greenhouse Gas		Global Warming Potential (GWP)
1.	Carbon dioxide (CO_2)	1
2.	Methane (CH_4)	29.8
3.	Nitrous oxide(N_2O)	273
4.	Hydrofluorocarbons (HFCs)	5 – 14,600
5.	Perfluorocarbons (PFCs)	78 – 12,400
6.	Sulfur hexafluoride (SF_6)	25,200
7.	Nitrogen trifluoride (NF_3)[3]	17,400

Figure 2-39: GWP of Greenhouse Gases

For instance, if 1 kg of methane is emitted, it can be represented as 29.8 kg of CO_2e (1 kg CH_4 * 29.8 = 29.8 kg CO_2e).

" CO_2e " is extremely helpful since it combines different greenhouse gases into one number, so it's easier to compare their overall impact on global warming.

For the purpose of this thesis, the emissions of CH_4 and N_2O (in kt) will be converted to CO_2e:

- 1 [kt] of Methane CH4 → 29.8 [kt] of CO_2e
- 1 [kt] of Nitrous Oxide N_2O → 274 [kt] of CO_2e

In the following sections, the mainstream alongside all its sub streams will be clearly divided in tiers to construct a multi-tier architecture. After outlining the different levels of the system from root to top, the blockchain system's parameters will be explained. These parameters include:

- The elements and the properties of the blocks.
- The links between the blocks, and between the blocks and the blockchain.
- The functional parameters of the blocks.

Tier 1 (Batches): In the top-tier the product is the main-stream of natural gas. As explained before, this product consists of different sub-streams (**batches**). These sub-streams might vary on factors concerning the extraction and processing location, the undergone processing, but they all have the same thing in common, the volume. Each of these sub-streams carries data concerning emissions from all the different processes this stream has gone through.

The three streams depicted in Figure 2-40 combine into the main stream, and the emissions they contain are added together.

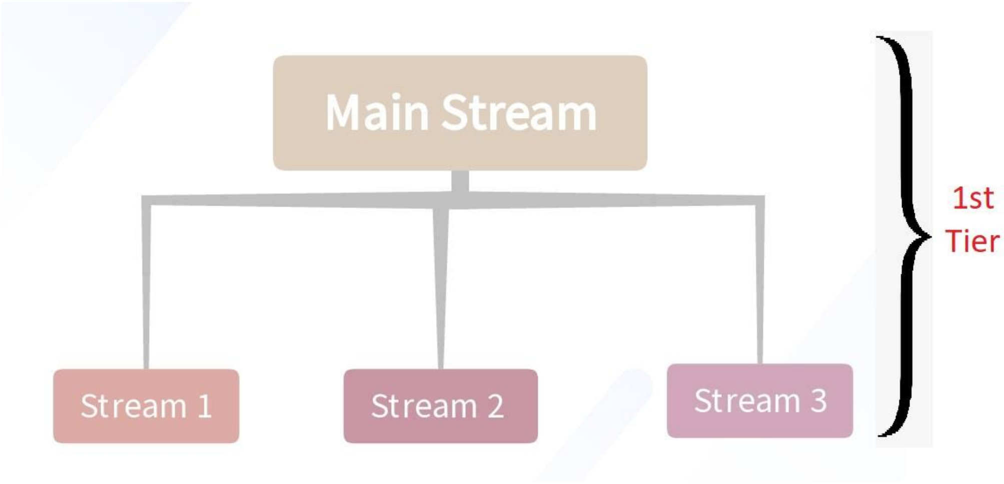


Figure 2-40: Natural Gas System 1st Tier

Tier 2 (Stages): In the Torchlight example, the 2nd tier illustrated the emissions generated during the manufacturing of the sub-components that make up the components of the 1st tier.

In the Natural Gas example, the streams do not consist of other sub-streams (sub-components) since they fundamentally remain the same from extraction to distribution. However, they undergo several processes for their refining. As explained in section 2.1.1 these processes can be categorized in the following **Stages**:

- Exploration
- Production
- Processing
- Transmission and Storage
- Distribution

The emissions caused by these **Stages**, as depicted in figure 2-41, merge in each of the 1st tier's streams, and the emissions that they contain are summed.

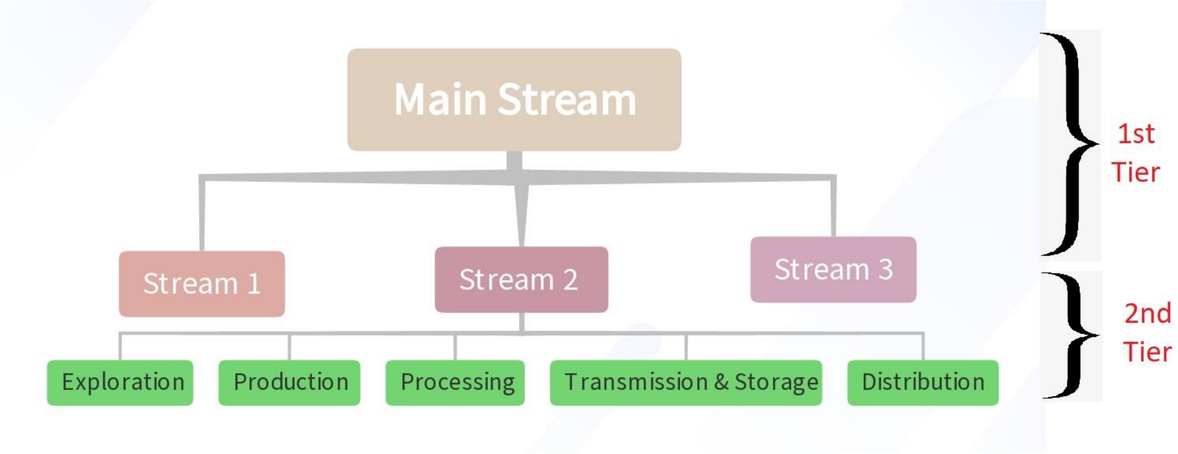


Figure 2-41:Natural Gas System 2nd Tier

Tier 3 (Processes): This tier comprises the **Process Groups** that make up each **Stage** within tier 2. For instance, "**Production**" Stage consists of the following Process Groups:

- Gas Wells
- Well Pad Equipment
- Well Workovers
- Produced Water
- Normal Operations
- Condensate Tank Vents
- Compressor Exhausts Vented
- Blowdowns
- Upsets
- Gathering and Boosting

The emissions caused by these **Process Groups**, as depicted in figure 2-42, merge in each of the 2nd tier's stages, and the emissions that they contain are summed.

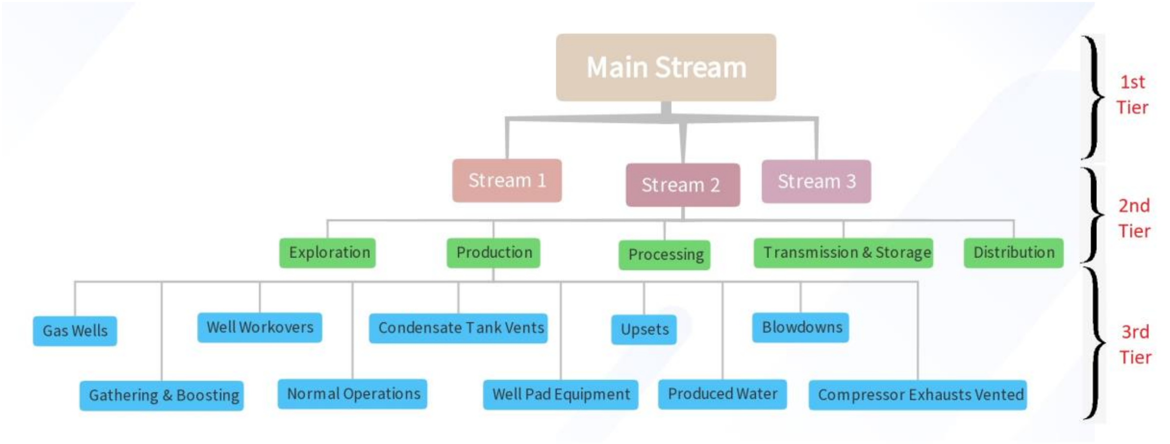


Figure 2-42: Natural Gas System 3rd Tier

Tier 4: This is the root tier of this multi-tier architecture. This tier comprises the **Processes** that make up each **Process Group** within tier 3. For instance, the "**Well-Pad Equipment"** process consists of:

- Heaters
- Separators
- Dehydrators
- Meters/Piping
- Compressors

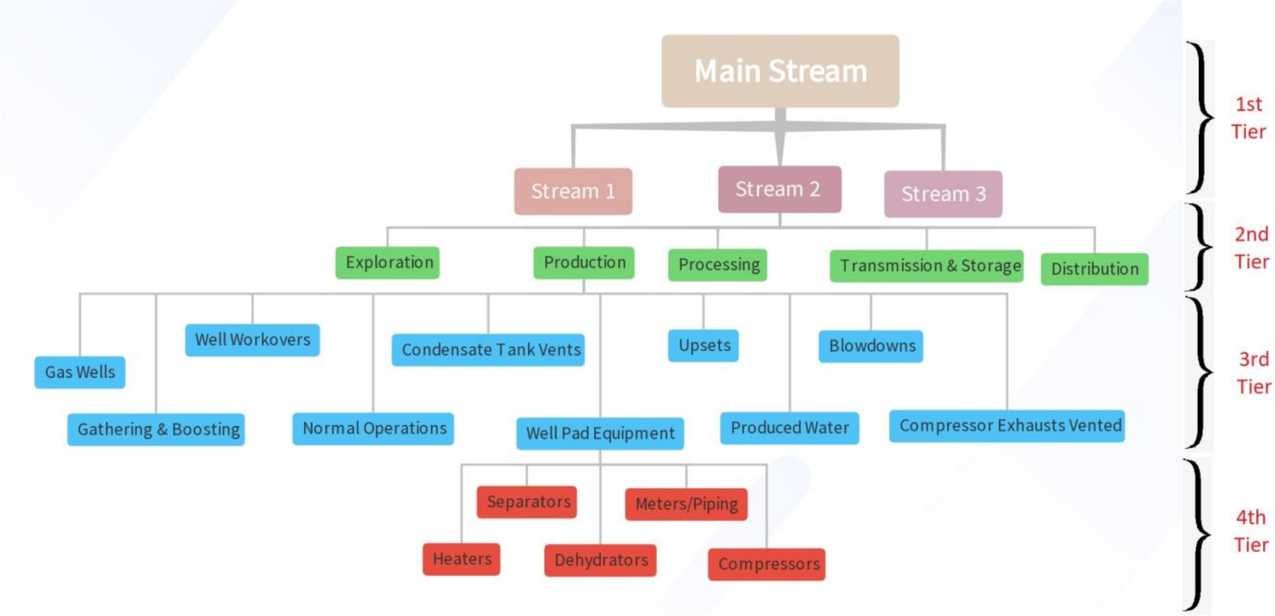


Figure 2-43:Natural Gas System 4th Tier

The emissions caused by these **Processes**, as depicted in figure 2-43, merge in each of the 3rd tier's **Process Groups** and the emissions that they carry are summed.

Figure 2-43 presents the full architecture of Natural Gas's supply chain. It has been based on the mapping of emissions by EPA's **"US GHG-Inventory"** [42], and provides the foundation for the creation of an integrated blockchain system.

The different characteristics of such a system, such as block and blockchain structure, will be described. However, and because of the complexity and size of such a system, for the purpose of this thesis, a simpler architecture will be presented in the next chapter. This architecture was based on the basin-level emissions analysis of the **"Inventory of U.S Greenhouse Gas Emissions and Sinks"** [42] . This architecture will be later implemented in a pseudo-blockchain system that is compiled locally and simulates the processes of a distributed system.

2.2.4 Proposed Architecture of a Blockchain-Implemented Natural Gas System

The purpose of this section is the design of the functional parameters and the architecture of a simplified blockchain system for the emissions of natural gas supply chain system. This system will be later implemented into a pseudo blockchain application.

The proposed architecture is based on the update of “Inventory of U.S Greenhouse Gas Emissions and Sinks” [1] that incorporates additional basin-level data, as explained in section 2.1.2.

In this scenario, it is first necessary to establish the parameters for the batches, similar to what was detailed in Section 2.2.3.

1) Product

In Section 2.2.3, the final product was the **main-stream** (the main network of pipelines) in which all the sub-streams (batches or in this case basins) ended up.

In this case, the final product represents **the total US emissions** caused by the operation of the Natural Gas Systems.

2) Batches

The batches are defined as the emissions caused from different streams of natural gas that merge into the total US Emissions. The batches are defined as follows:

- **Batch Origin:** Each batch represents the emissions from a stream that originates from a **specific basin**. For example, New England Province, Atlantic Coast, Florida Platform etc.
- **Batch Characteristics:** It is assumed that the sub-streams that were merged in a unified basin stream have similar characteristics, such as composition, quality, and processing requirements.
- **Batch Quantity:** Each batch is quantified based on the time interval of one year. They represent the total emissions per basin, per year.

These admissions were made from the emissions data collected in the “Inventory of U.S Greenhouse Gas Emissions and Sinks” [1], that are grouped:

- Yearly from year **1990 – 2021**.
- Per each of the **96 U.S Basins**.

3) Units of Measurement

The yearly basin level emissions in CH_4 and CO_2 are presented in kilotons. Therefore, like Section 3.2.1.3 each kiloton of methane will be converted into CO_2e as follows:

- 1 [kt] of Methane CH4 → 29.8 [kt] of CO_2e

In this analysis, the emissions of the streams (batches) from 2 different basins will be examined. These basins are:

- **Illinois Basin**: The basin that is centred in and underlying most of the state of Illinois and extending into southwestern Indiana and western Kentucky.
- **Arkoma Basin**: The peripheral foreland basin that extends from central west Arkansas to southeastern Oklahoma.

A) **CH_4** emissions from Natural Gas Systems.

Tier 1 (Batches): At the top-tier of this multi-tier system, the product is **the Yearly Total US Emissions** caused by the operation of Natural Gas Systems. As explained before, **the Yearly Total US Emissions** consist of the yearly emissions from all 96 basins (Batches).

Since all the 96 different basins (Batches) cannot be illustrated in figures, only Illinois and Arkoma will be displayed.

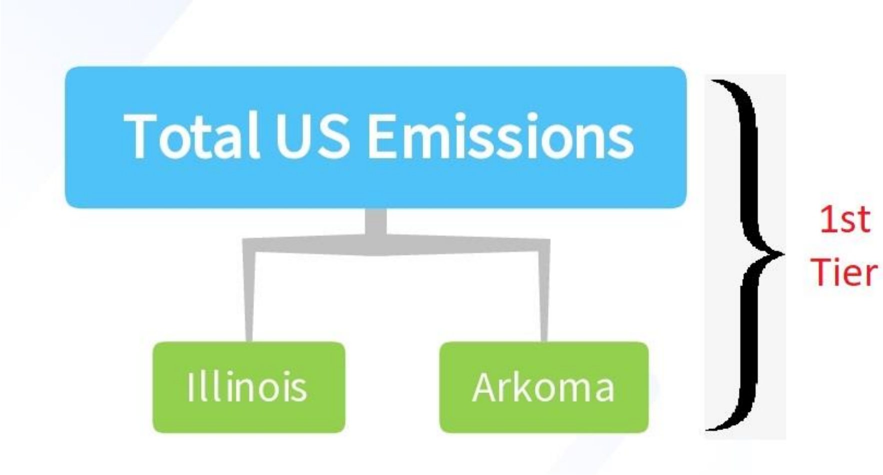


Figure 2-44: Proposed Natural Gas System's 1st tier: Batches.

Tier 2 (Process Groups): The emissions within the Illinois and Arkoma basins (batches) are generated by the refining processes within Natural Gas Systems, and these processes are categorized into **Process Groups**. Figure 2-45 provides an illustration of the tier 2 Process Groups.:

1. **Well Pad Equipment Leaks**
2. **Chemical Injection Pumps**
3. **Pneumatic Controllers**
4. **Tanks**
5. **Liquids Unloading**

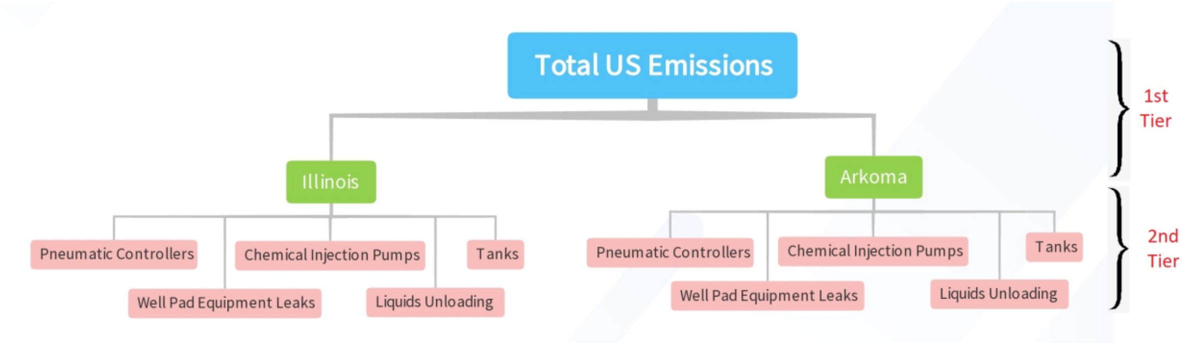


Figure 2-45: Proposed Natural Gas System's 2nd tier: Process Groups.

Tier 3 (Processes): This is the root tier of this multi-tier architecture. This tier comprises the **Processes** that make up each **Process Group** within tier 2. These Processes have been thoroughly explained in Section 2.1.2, and are presented in figure 2-46:

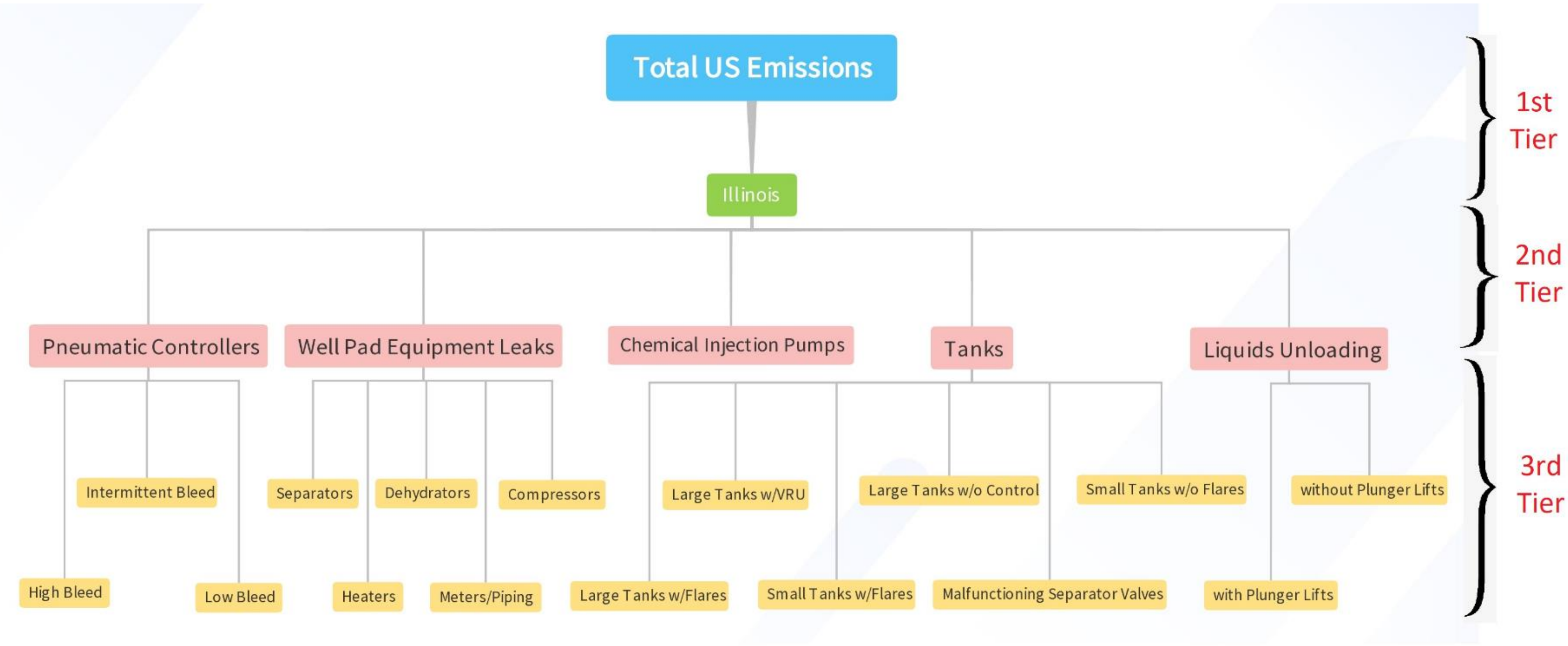


Figure 2-46: Proposed Natural Gas System's 3rd tier: Processes.

These Processes are the same for the Arkoma Basin but have not been demonstrated due to lack of space.

It is apparent that in comparison to the Architecture of Section 2.2.3, the tier **Stages** has been emitted, and the number of total processes has been decreased.

This represents the final architecture upon which the blockchain application for this case study will be built.

B) **CO_2** emissions from Natural Gas Systems:

According to the “Inventory of U.S Greenhouse Gas Emissions and Sinks” [1], the CO_2 emissions concern only the emissions by the following Process Groups of Tier 2:

- Tanks
- Liquids Unloading

As figure 2-47 suggests, the total emissions from the Liquids Unloading Process Group will be calculated by adding together both CO_2 and CH_4 emissions, which have been converted to CO2e (carbon dioxide equivalent):

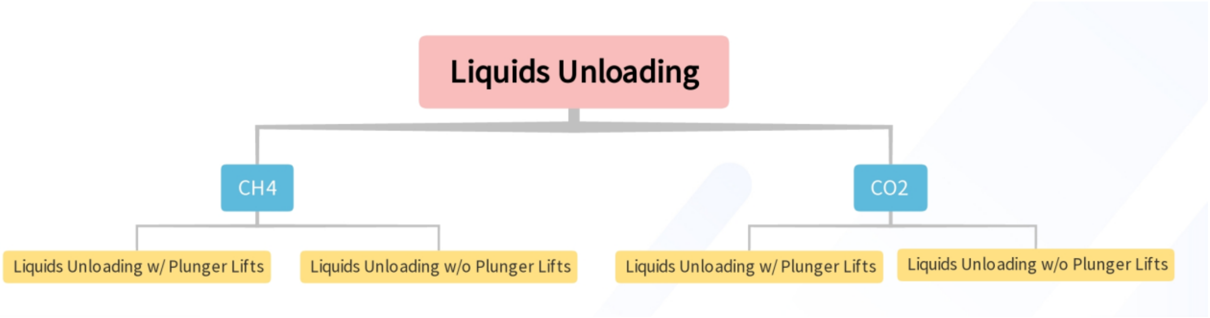


Figure 2-47: Combination of CH4 and CO2 emissions

The same procedure will be carried out in the case of Tanks.

Chapter 3 : Case Study: Blockchain Application

The developed blockchain application is a pseudo-application that is stored locally. This means that it is not distributed to a network of users. It is meant to simulate the functionality of an actual blockchain network and provide an initial approach to this thesis case study. This project adheres to the principles of Blockchain technology, and it is scalable meaning that it can be further developed to a deployable application.

This application has been developed on C# which is a versatile, modern, object-oriented programming language developed by Microsoft. It is widely used for the creation of software applications, including desktop, web, mobile, cloud-based, and gaming applications [51]. Some of the features of C# are:

- **Object Oriented**: supporting features like classes, objects, inheritance, encapsulation, and polymorphism.
- **Syntax and Structure**: C# has a syntax that is similar to other C-style languages and Java.
- **Platform Independence**: C# applications can be developed to target multiple platforms.
- **.NET Framework and .NET Core:** .NET provides a vast class library with pre-built functions for common tasks.
- **Language Features**: C# offers a variety of features, including properties, events, delegates, lambda expressions etc which enhance code readability, modularity, and flexibility.
- **Garbage Collection**: Memory management in C# is handled by an automatic garbage collection mechanism and provide ease of use the developer.
- **Enums and Structs**: In addition to classes, C# provides enums (enumerations) and structs (value types).

The above features will be widely utilized in this application since they provide flexibility and ease of use.

In the following sections the structure of transactions, blocks and the unique features of this application will be described. At the end, the results of this application will be presented.

3.1 Transactions

The blockchain consists of blocks. Each block contains the emissions from a process, or a set of processes of the lowest tier.

For instance, a block can contain the emissions from just the heaters, or from the heaters, compressors, and dehydrators.

For this thesis, the emissions deriving from root tier processes will be called **transactions.**

Transactions:

In general, a transaction is a completed agreement between a buyer and a seller to exchange goods, services, or financial assets in return for money [52].

In the case of blockchain, and specifically for **bitcoin**, Transactions are data structures that encode the transfer of value between participants in the bitcoin system [53].

The journey of a transaction begins when it's made, which is called "origination." After that, it gets signed to show it's valid, like a stamp of approval to spend the money involved. The transaction is then sent out to the Bitcoin network, where a lot of computers check it to make sure it's real. Once they all agree, a special computer confirms it and puts it in a block with other transactions. This block is added to the digital record called the blockchain.

Once the transaction is in the blockchain and a bunch of other blocks are added after it, it becomes a permanent part of the Bitcoin record that everyone trusts. The money moved in the transaction can now be used by someone else in a new transaction, starting the process all over again.

Transactions in the Natural Gas Blockchain refer to data structures that encode the transfer of the value of emissions from the network’s manufacturers to the decentralized blockchain.

Some examples of Transactions are presented as follows:

- A **Processing Plant** submits a transaction of emissions to the blockchain that refers to **Dehydrator** emissions and belongs to **Batch 5** (originating from San Juan Basin).
- An **Extraction Point** submits a transaction of emissions to the blockchain that refers to **Liquids Unloading** emissions and belongs to **Batch 6** (originating from Llano Uplift Basin).
- A **Compressor Station** along the distribution network submits a transaction of emissions to the blockchain that refers to **Compressors** emissions and belongs to **Batch 1** (originating from Las Vegas-Raton).

Once each of these transactions is verified, a special computer confirms it and puts it in a block with other transactions.

The block will be later processed and added to the blockchain.

The properties of each transaction have been added in a C# class called “**Emissions”** and contain:

1) **BatchNo [integer]**: This property is the UniqueID of the **Batch** that the transaction belongs to, as described in tier 1. In total there are 96 different Batch numbers, one for each stream. The data type is **integer** with a range of 0-95 that derives from the following Enum:

```
public enum Batches //Each value represent the origin of the stream
{
    NewEnglandProvince = 0,
    AdirondackUplift = 1,
    AtlanticCoast = 2,
    SGASedimentaryProv = 3,
    FloridaPlatform = 4,
    PiedmontBlueRidgeProv = 5,
    Appalachian = 6,
    AppalachianEastb = 7,
    BlackWarrior = 8,
    MidGulfCoast = 9,
    GulfCoast = 10,
    Arkla = 11,
    UpperMississippiEmbaymnt = 12,
    .
    .
    .
    NorthernFoothillsProvince = 94,
    ArcticCoastalPlainsProvince = 95
}
```

Figure 3-1: Batch Enum

2) **Group [string]:** This property represents the Process Groups as described tier 2. The data type is **string** that derives from the following Enum:

```
public enum ProcessGroup
{
    PneumaticControllers,
    WellPadEquipmentLeaks,
    ChemicalInjectionPumps,
    Tanks,
    LiquidsUnloading
}
```

Figure 3-2: Process Group Enum

3) **Process [string]:** This property represents the **Process** of the transaction as described in tier 3. The data type is **string** that derives from the following Enum:

```
public enum Process
{
    Separators,
    Heaters,
    Dehydrators,
    MetersPiping,
    Compressors,
    HighBleed,
    LowBleed,
    IntermittentBleed,
    LargeTankswVRU,
    LargeTankswoControl,
    SmallTankswoFlares,
    MalfunctioningSeparatorDumpValves,
    LargeTankswFlares,
    SmallTankswFlares,
    LiquidsUnloadingwPlungerLifts,
    LiquidsUnloadingwoPlungerLifts
}
```

Figure 3-3: Process Enum

4) **CH_4Emissions [double]:** This property represents the amount of CH_4 emissions in kilotons that were released by the process.
5) **CO_2Emissions [double]:** This property represents the amount of CO_2 emissions (if any) in kilotons that were released by the process.
6) **CO_2e [double]:** This property represents the total emissions that derive from the sum of both CO_2 and CH_4, converted to CO_2e. It is expressed as follows:

```
CO2e = CO2Emissions + 29.8 * CH4Emissions;
```

The complete transactions class is presented as follows:

```
public class Emissions
{
    public int BatchNo { get; set; }
    public ProcessGroup Group { get; set; }
    public Process Process { get; set; }
    public double CH4Emissions { get; set; }
    public double CO2Emissions { get; set; }
    public double CO2e { get; set; }

       public Emissions(int batchNo, ProcessGroup group, Process process, double
       ch4Emissions, double co2Emissions, double co2e)

       {
          BatchNo = batchNo;
          Group = group;
          Process = process;
          CH4Emissions = ch4Emissions;
          CO2Emissions = co2Emissions;
          CO2e = CO2Emissions + 29.8 * CH4Emissions;
       }

}
```

Figure 3-4: Transaction (Emissions) Class

An instance of the “Emissions” class (**Object**) is created as follows:

```
Emissions LargeTanks = new Emissions((int)Batches.Arkoma, ProcessGroup.Tanks,
                                     Process.LargeTankswFlares, 10.0, 0.0, 0.0);
```

Figure 3-5: Instance of an Emissions Class

This Transaction has the following properties:

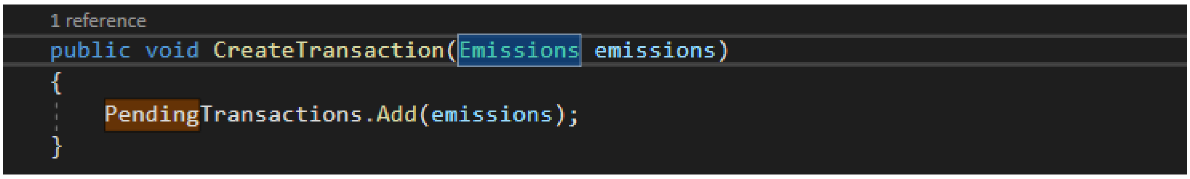
1) **BatchNo [integer]** = 19
2) **Group [string] =** Tanks
3) **Process [string] =** LargeTankswFlares
4) **CH_4Emissions [double]:** 10 [kt].
5) **CO_2Emissions [double]:** 0 [kt].
6) **CO_2e [double]:** 298 [kt]:

In order to create the transaction of the previous example the method **CreateTransaction()** is called as follows:

```
USEmissions.CreateTransaction(new Emissions((int)Batches.Arkoma, ProcessGroup.Tanks,
                                            Process.LargeTankswFlares, 10.0, 0.0, 0));
```

Figure 3-6: Create Transaction Function Call

This method adds this transaction to a list called **PendingTransactions.** This list contains all the transactions that have been submitted to the blockchain network but **have not yet been put into blocks and processed**.



```
1 reference
public void CreateTransaction(Emissions emissions)
{
    PendingTransactions.Add(emissions);
}
```

Figure 3-7: Pending Transactions

3.2 Blocks

A transaction, or a set of transactions, as described in Section 3.1 are processed and added into Blocks, the structural components of the blockchain.

3.2.1 Block Structure

As stated in the introductory chapters of this thesis the blockchain consists of a chain of blocks. This case study implemented the architecture presented in Figure 3-8 [54]:

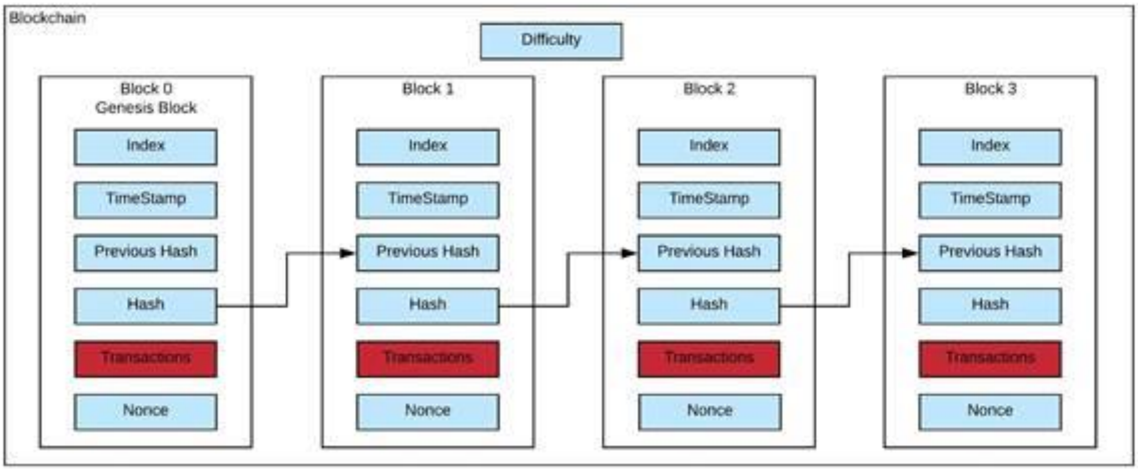
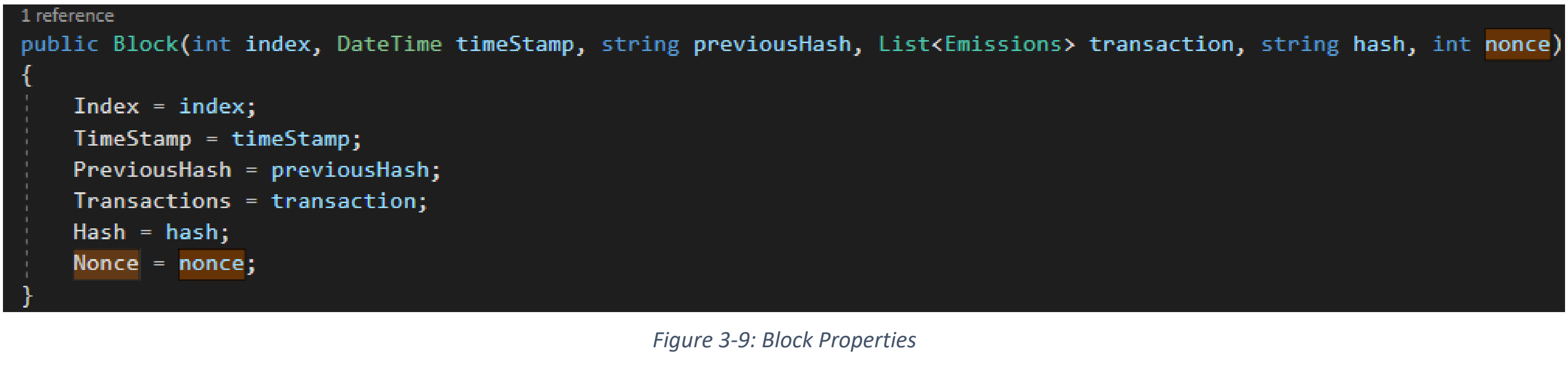


Figure 3-8: Blockchain Architecture

Each block has the following properties.

- **Index [Integer]**: A **uniqueID** that represents the number of the Block. Ranges from 0 - ∞
- **Timestamp [DateTime]**: The Date and Time of the Block's submission into the Blockchain. Utilizes method **DateTime.Now()**;
- **Previous Hash [string]**: Explained in Section 3.2.2
- **Hash [string]**: Explained in Section 3.2.2
- **Transactions [Emissions]**: The list of **PendingTransactions** that have been submitted but not yet processed.
- **Nonce [int]:** Explained in Section 3.2.2



```
1 reference
public Block(int index, DateTime timeStamp, string previousHash, List<Emissions> transaction, string hash, int nonce)
{
    Index = index;
    TimeStamp = timeStamp;
    PreviousHash = previousHash;
    Transactions = transaction;
    Hash = hash;
    Nonce = nonce;
}
```

Figure 3-9: Block Properties

3.2.2 Hash and Mining

Hash:

In general, the block’s **hash** is a unique identifier for each block, generated by applying a cryptographic hash function to the block's data. It's like a digital fingerprint for the block [55]. It ensures the integrity and security of the blockchain by preventing tampering. It links blocks together in sequential order, forming a reliable transaction history. It is extremely important in the maintenance of the immutability and trustworthiness of the blockchain network.

In this case, the block’s hash is created using cryptographic hash function **SHA-256** (Secure Hash Algorithm 256-bit). The process involves taking the block's data and applying the hash function to produce a unique hash output. These data are:

- **Timestamp**: It denotes the moment of block creation or addition to the blockchain, pointing out the time-based sequence to the blocks.
- **Previous hash**: This hash corresponds to the preceding block within the blockchain, connecting the present block to its precursor and assuring the orderly progression of blocks.
- **Transactions**: Also known as Merkle Root, all the transactions that are contained in the block are serialized and affect the created hash.
- **Nonce**: A unique number that helps miners solve the puzzle needed to add a new block to the blockchain.

The Block’s hash is created by calling the **CalculateHash()** function:

```
5 references
public string CalculateHash()
{
    SHA256 sha256 = SHA256.Create();

    byte[] inputBytes = Encoding.ASCII.GetBytes($"{TimeStamp}-{PreviousHash ?? ""}-{JsonConvert.SerializeObject(Transactions)}-{Nonce}"); ;
    byte[] outputBytes = sha256.ComputeHash(inputBytes);

    return Convert.ToBase64String(outputBytes);
}
```

Figure 3-10: Calculate Hash Function

The steps that this function follows to create a hash are presented below:

- It creates a SHA-256 hash algorithm instance.
- It converts specific block-related information (timestamp, previous hash, transactions, and nonce) into bytes.
- It uses the SHA-256 algorithm to process these bytes and generate an output hash in the form of bytes.
- Finally, the output hash bytes are converted into a base64-encoded string, which represents the calculated hash.

Previous Hash:

The Previous Block's Hash plays a pivotal role in maintaining the integrity and the sequential continuity of the blockchain. This property, ensures that a robust linkage is established between blocks, forming an unbroken chain of transactions.

This connection makes it so that if someone tries to change a block, they will also have to change all the blocks that come after it, since the Previous Block property is involved in the hash creation of the later blocks as Figure 3-8 suggests.

In the case that an attacker recalculates the hashes of the current block and all the following blocks, the verification could theoretically pass. However, this would only pass on one node (his node) because Blockchain is a decentralized system.

However, in this case, there is a stronger weapon in dealing with tampering.

Proof of Work (Mining):

Proof of Work is a method employed to produce a new block in a blockchain, demanding substantial computational time to generate a piece of data for the new block. The resulting data should be straightforward and easy to verify, allowing nodes within the network to readily confirm its authenticity.

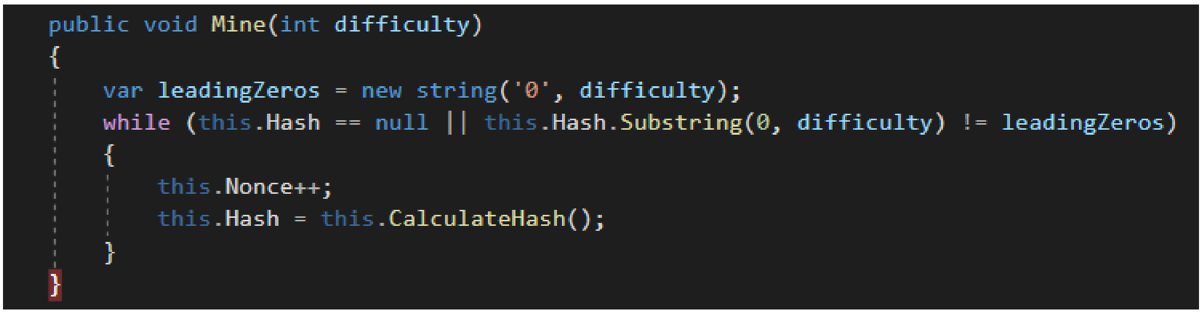
The generated information serves as evidence that the block is valid, and effort went into making it. The work needed to create a new block is calculated based on the average time it takes to generate a new block across the entire blockchain network.

The algorithm picked to implement Proof of Work scheme is a hash algorithm. The most widely used hash algorithm in Proof of Work is SHA-256.

In Proof of Work, or mining, the generated hash has a specific format.

For example, in this implementation, each hash should have a number of leading zeros. This is a very computing intensive and time-consuming process, and there is no shortcut for the generating process.

The function used to mine the blocks is the **Mine()**:



```
public void Mine(int difficulty)
{
    var leadingZeros = new string('0', difficulty);
    while (this.Hash == null || this.Hash.Substring(0, difficulty) != leadingZeros)
    {
        this.Nonce++;
        this.Hash = this.CalculateHash();
    }
}
```

Figure 3-11: Mine function

The variable **difficulty** determines the number of leading zeros. As the number of leading zeros increases, the computing time increases exponentially. For example, it has been measured that a laptop with a “Intel(R) Core(TM) i7-10510U CPU @ 1.80GHz 2.30 GHz” Processor and 16.0 gb of RAM, achieved the following Computing Times:

- Computing Time with difficulty 1: **0 milliseconds** (Cannot count less than milliseconds)
- Computing Time with difficulty 2: **24 milliseconds**
- Computing Time with difficulty 3: **2813 milliseconds**
- Computing Time with difficulty 4: **42735 milliseconds**

It is obvious that as the number of leading zeroes increases, the computing time increases exponentially.

This makes it hard for anyone to tamper with the blocks because it would take a lot of computing power, and time.

Moreover, in the **Mine()** function a new variable name Nonce is introduced.

Nonce:

In mining, a "nonce" is a unique number that miners change and add to the block's data. They then repeatedly hash this data until they find a hash that meets specific criteria, often starting with a certain number of zeros.

Essentially, the **CalculateHash()** function is repeatedly called during the mining process, with each call using a different nonce value (incremented by 1, as demonstrated in Figure 3-11), until the hash meets the required criteria.

The nonce helps miners solve the puzzle needed to add a new block to the blockchain. It's like a secret code they tweak until they get the right result.

3.3 Blockchain

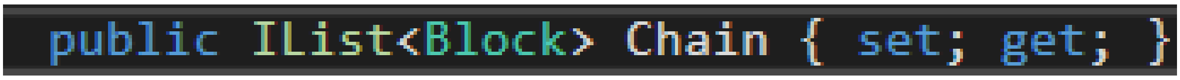
The blockchain operates as a record book that collects all the US Emissions per Year. It consists of multiple blocks that contain multiple transactions that are all added together to produce the total US Emissions. This Section thoroughly describes the Blockchain's features by focusing on the following points:

- Initiation Parameters and Genesis Block
- Block Addition
- Validation
- I/O
- Examples and Data Filtering

3.3.1 Initiation Parameters and Genesis Block

The Blockchain has been declared as a C# IList<Block>, whose elements are Blocks (Figure 3-12).

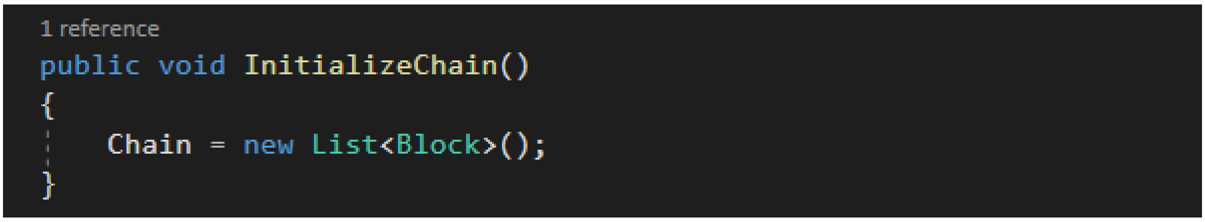
In C#, an **IList** is an interface that represents a collection of objects that can be accessed by index. This interface allows developers to perform operations like adding, removing, and accessing items based on their position in the list. [56]



```
public IList<Block> Chain { set; get; }
```

Figure 3-12: Chain's Object

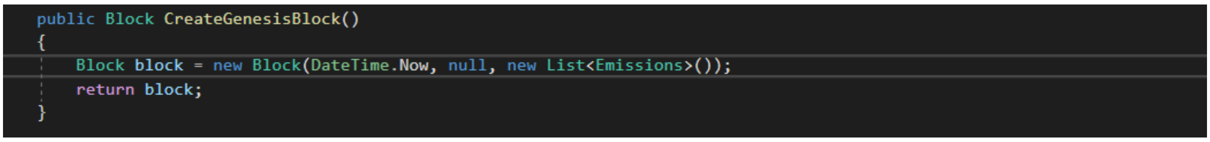
The Chain is initialized by **InitializeChain()** method:



```
1 reference
public void InitializeChain()
{
    Chain = new List<Block>();
}
```

Figure 3-13: Chain's Instantiation

Beyond the instantiation of the Chain, the initiation is about creating the first block of the chain called Genesis Block. This is an empty from data block, that just provides the first Hash and Index of the Chain.



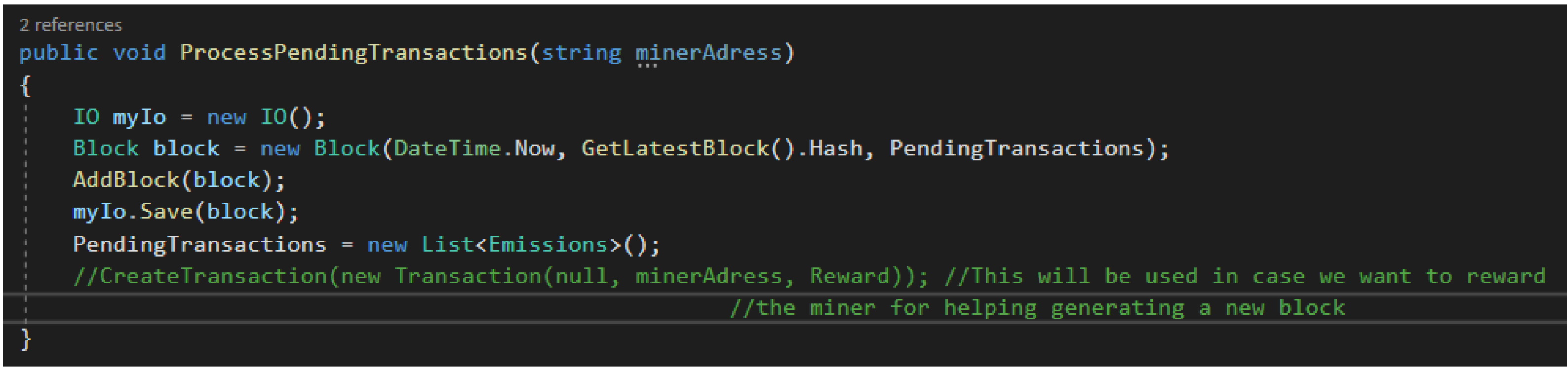
```
public Block CreateGenesisBlock()
{
    Block block = new Block(DateTime.Now, null, new List<Emissions>());
    return block;
}
```

Figure 3-14: Method that creates the Genesis Block

- The properties of PreviousHash, Nonce, Transactions are null.
- The only value that affects the Hash is the Timestamp of the Genesis Block's creation.
- No mining is performed on this block.

3.3.2 Block Addition

Adding a new block requires processing the list of transactions that are stored in the **“PendingTransactions”** list so that the criteria to be added to the blockchain are met. This is performed by calling a method called **ProcessPendingTransactions():**



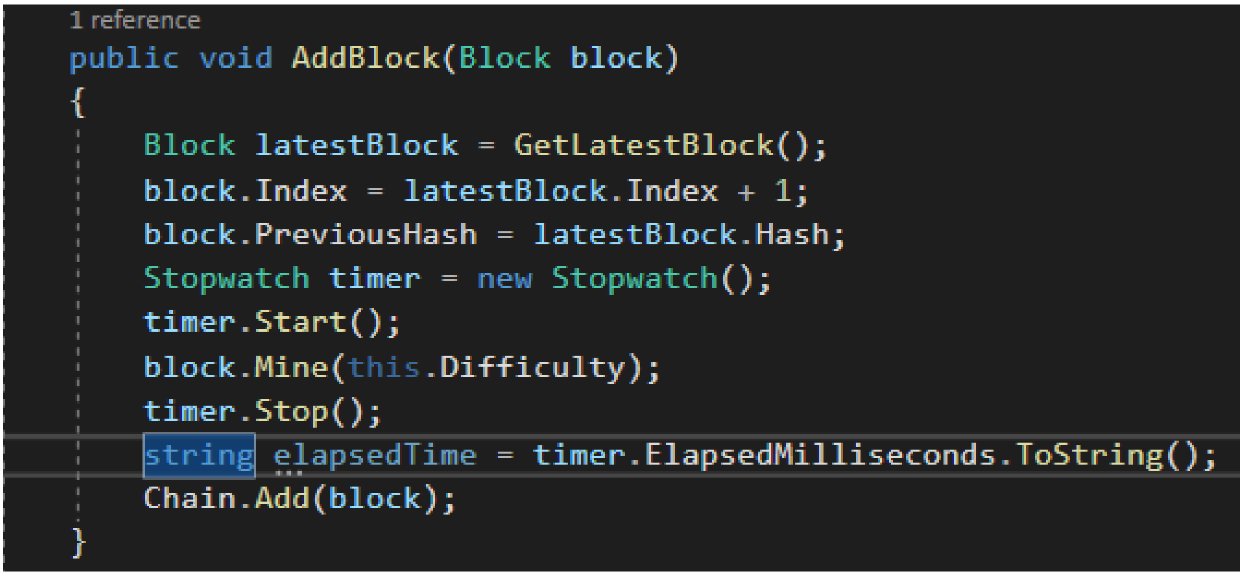
```
2 references
public void ProcessPendingTransactions(string minerAdress)
{
    IO myIo = new IO();
    Block block = new Block(DateTime.Now, GetLatestBlock().Hash, PendingTransactions);
    AddBlock(block);
    myIo.Save(block);
    PendingTransactions = new List<Emissions>();
    //CreateTransaction(new Transaction(null, minerAdress, Reward)); //This will be used in case we want to reward
                                                     //the miner for helping generating a new block
}
```

Figure 3-15: Process Pending Transactions

This method:

1. **Creates a new block**: A new block is being created with the following parameters:
    a. The current date and time.
    b. The hash of the latest block in the chain.
    c. The list of pending transactions.
2. **Adds the new block to the blockchain:** The newly created block is added to the blockchain using the **AddBlock(block)** method. This method is responsible for validating the block and integrating it into the blockchain.
3. **Saves the block**: The newly created block is being saved using the IO object's Save method.
4. **Clears pending transactions**: After the Block creation and addition to the chain the list of pending transactions is reset to an empty list.
5. **Optional**: The comment mentions that the **CreateTransaction()** method could potentially be used to reward the miner for generating a new block. However, this is not currently being used.

As mentioned before, the **AddBlock()** method is responsible for validating the block and integrating it into the blockchain:



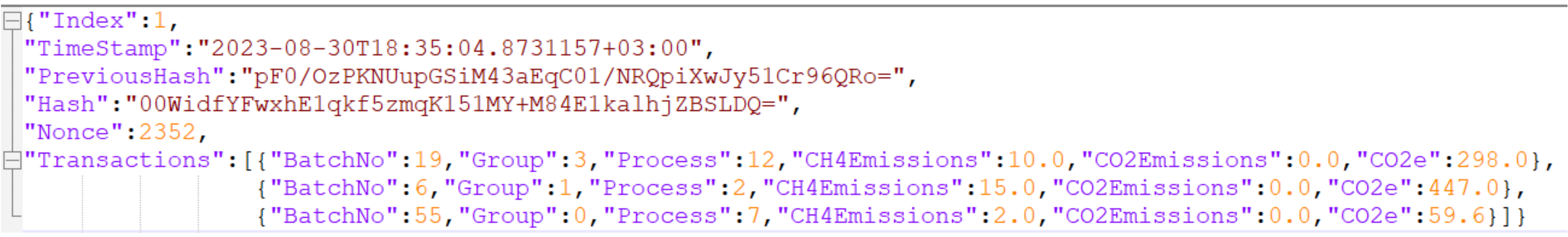
```
1 reference
public void AddBlock(Block block)
{
    Block latestBlock = GetLatestBlock();
    block.Index = latestBlock.Index + 1;
    block.PreviousHash = latestBlock.Hash;
    Stopwatch timer = new Stopwatch();
    timer.Start();
    block.Mine(this.Difficulty);
    timer.Stop();
    string elapsedTime = timer.ElapsedMilliseconds.ToString();
    Chain.Add(block);
}
```

Figure 3-16: Add Block Method

This method:

1. **Gets the latest block**: The function starts by obtaining the latest block in the blockchain using the **GetLatestBlock()** method.
2. **Assigns block index and previous hash**: The index of the incoming block is set to be one greater than the index of the latest block, and the PreviousHash property of the block is assigned the hash of the latest block. These steps help maintain the chronological order and link between blocks.
3. **Starts a stopwatch**: A Stopwatch object is initiated to measure the time taken for mining the block.
4. **Mines the block**: The Mine() method explained in Section 3.2.2, is called.
5. **Stops the stopwatch:** The stopwatch is stopped after the mining process is complete, and the elapsed time is recorded.
6. **Adds the block to the blockchain:** The block is added to the blockchain by appending it to the Chain (assuming Chain is a collection that maintains the blockchain).

An example of an added block, saved in JSON format (Explained in Section 3.3.4), is presented below:



```
{"Index":1,
"TimeStamp":"2023-08-30T18:35:04.8731157+03:00",
"PreviousHash":"pF0/OzPKNUupGSiM43aEqC01/NRQpiXwJy51Cr96QRo=",
"Hash":"00WidfYFwxhE1qkf5zmqK151MY+M84E1kalhjZBSLDQ=",
"Nonce":2352,
"Transactions":[{"BatchNo":19,"Group":3,"Process":12,"CH4Emissions":10.0,"CO2Emissions":0.0,"CO2e":298.0},
                {"BatchNo":6,"Group":1,"Process":2,"CH4Emissions":15.0,"CO2Emissions":0.0,"CO2e":447.0},
                {"BatchNo":55,"Group":0,"Process":7,"CH4Emissions":2.0,"CO2Emissions":0.0,"CO2e":59.6}]}
```

Figure 3-17: Block Example

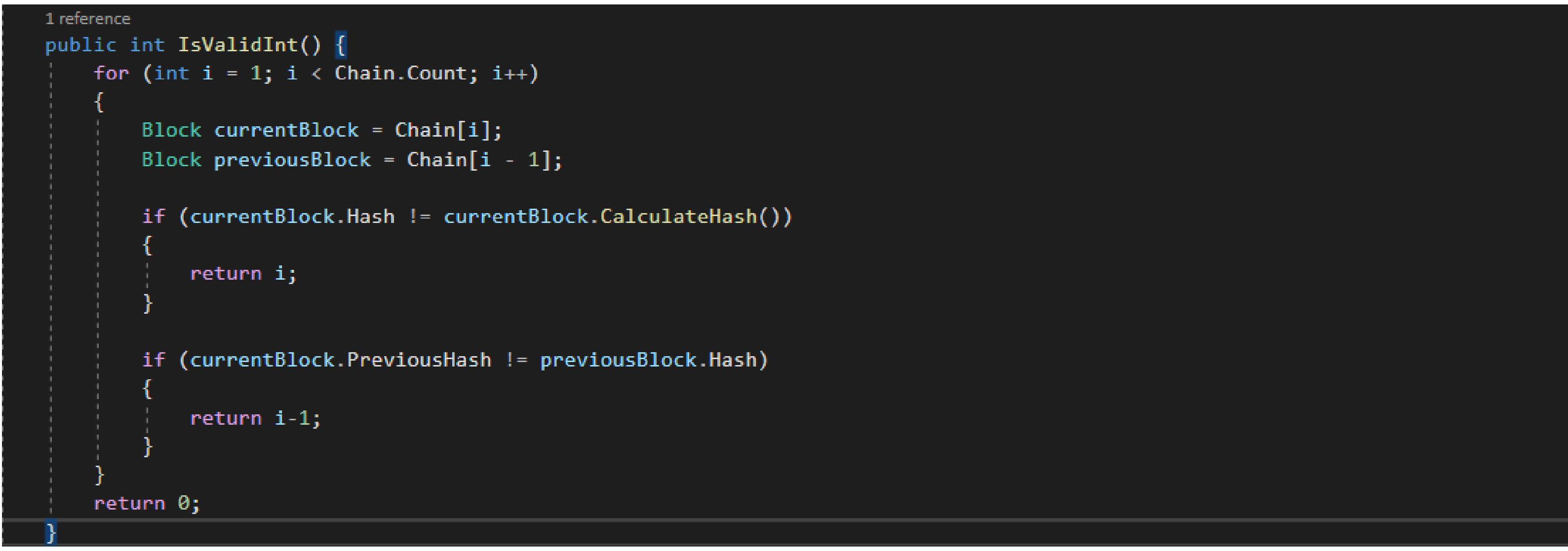
This Block contains the following transactions:

1. **10 [kt]** of **CH_4** from the **Arkoma** Batch (No.19), caused by Process **LargeTankswFlares** (No.12), that belongs to Group **Tanks** (No.3)

2. **15 [kt]** of **CH$_4$** from the **Appalachian** Batch (No.6), caused by Process **Heater** (No.2), that belongs to Group **WellPadEquipmentLeaks** (No.1)
3. **2 [kt]** of **CH$_4$** from the **GreenRiver** Batch (No.55), caused by Process **IntermittentBleed** (No.7), that belongs to Group **PneumaticControllers** (No.0)

3.3.3 Validation

A blockchain validation function is a mechanism used to verify the integrity and correctness of a blockchain. Its primary purpose is to ensure that the blocks within the blockchain are valid, have not been tampered with, and adhere to the predefined rules of the blockchain network. In this application, a recursive function has been created that examines all blocks of the blockchain and ensures that the required criteria are met.



```
public int IsValidInt() {
    for (int i = 1; i < Chain.Count; i++)
    {
        Block currentBlock = Chain[i];
        Block previousBlock = Chain[i - 1];

        if (currentBlock.Hash != currentBlock.CalculateHash())
        {
            return i;
        }

        if (currentBlock.PreviousHash != previousBlock.Hash)
        {
            return i-1;
        }
    }
    return 0;
}
```

Figure 3-18: Validation Function

This method:

1. **Loops Through All Blocks**.
2. **Checks Block Integrity**: For each iteration of the loop, the function retrieves the current block and the previous block.
3. **Verifies Current Hash**: It checks if the calculated hash of the current block matches the hash stored in the Hash property of the current block. If the calculated hash and the stored hash don't match, it indicates that the data within the block has been tampered with or altered.
4. **Verifies Previous Hash:** It verifies if the PreviousHash property of the current block matches the hash stored in the Hash property of the previous block.
5. **Returns Tampered Block Index**: If either the Hash of the current block doesn't match the calculated hash or the previous hash of the current block doesn't match the hash of the previous block, the function returns the index i. This index indicates the position in the chain where an inconsistency or tampering was detected.

6. **Returns 0 for Valid Chain:** If the loop completes without detecting any inconsistencies, the function returns 0. This signifies that the entire blockchain is valid and hasn't been tampered with.

3.3.4 I/O

I/O stands for "Input/Output." It refers to the process of interacting with devices, systems, or files to either receive information (input) or send information (output). In this Section, I/O refers to the Save and Load Process of the Blockchain. As mentioned before, the developed blockchain application is a pseudo – blockchain C# based program. This chain is stored locally in the user computer, meaning that it is not distributed. In fact, a folder has been created called “EmissionsBlocks” in which all the Chain’s blocks are stored in JSON format.

“JavaScript Object Notation (JSON)” is a data-exchange format that was developed due to the need of transferring populated data structures from any language to formats that are recognizable by other languages and platforms [57]. It is the descendant of markup languages such as XML. The syntax is simple, and the object’s properties can be easily parsed and serialized by software. An example of a basic JSON is the following:

```
{
  "Influencer": {"name": "Jaxon",  "age" : "42" ,  "city" ,  "New York"}
}
```

Figure 3-19: Simple JSON

JSON object data type is a set of name or value pairs inserted between {} (curly braces). The keys must be strings and should be uniquely separated by comma. JSON supports multiple data types such us:

- String
- Number
- Boolean
- Null
- Object
- Array

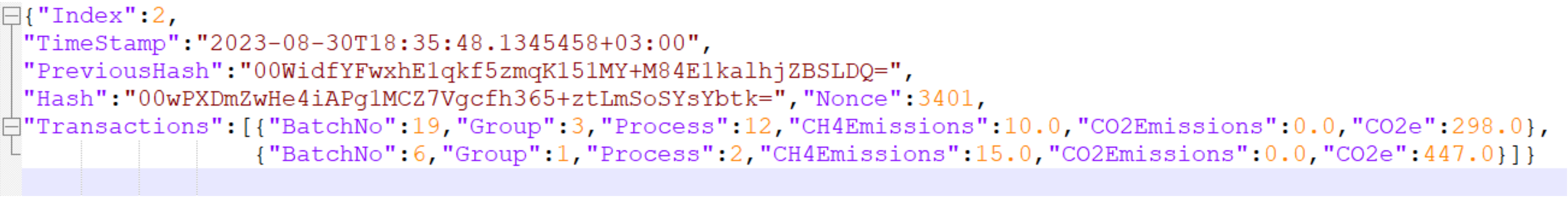
In a normal use case scenario, an ordered collection of multiple values called array is represented by a JSON object.

The syntax of an array, like the previous example is the following:

```
{
        "Influencers":[
        {
          "name" : "Jaxon",
          "age" : 42,
          "Works At" : "Tech News"
        }

        {
          "name" : "Miller",
          "age" : 35
          "Works At" : "IT Day"
        }]
}
```

Figure 3-20: JSON Examples

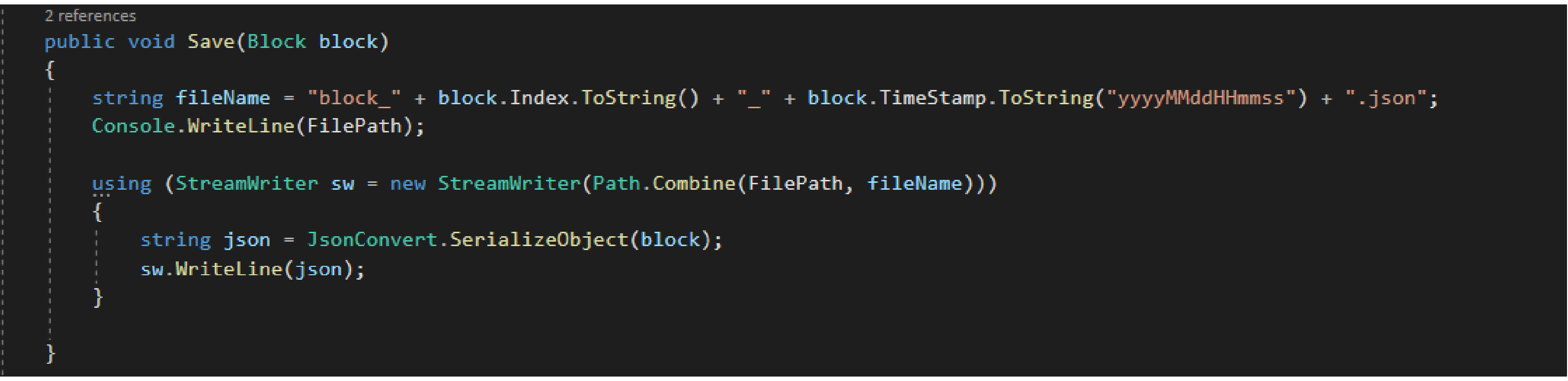
In this Application, the JSON format of the blocks is presented in Figure 3-64 and 3-68:



```
{"Index":2,
"TimeStamp":"2023-08-30T18:35:48.1345458+03:00",
"PreviousHash":"00WidfYFwxhE1qkf5zmqK151MY+M84E1kalhjZBSLDQ=",
"Hash":"00wPXDmZwHe4iAPg1MCZ7Vgcfh365+ztLmSoSYsYbtk=","Nonce":3401,
"Transactions":[{"BatchNo":19,"Group":3,"Process":12,"CH4Emissions":10.0,"CO2Emissions":0.0,"CO2e":298.0},
                {"BatchNo":6,"Group":1,"Process":2,"CH4Emissions":15.0,"CO2Emissions":0.0,"CO2e":447.0}]}
```

Figure 3-21: Block Example 2

These examples have been saved in the folder “EmissionsBlocks” using the method presented in figure 3-22:



```
2 references
public void Save(Block block)
{
    string fileName = "block_" + block.Index.ToString() + "_" + block.TimeStamp.ToString("yyyyMMddHHmmss") + ".json";
    Console.WriteLine(FilePath);

    using (StreamWriter sw = new StreamWriter(Path.Combine(FilePath, fileName)))
    {
        string json = JsonConvert.SerializeObject(block);
        sw.WriteLine(json);
    }

}
```

Figure 3-22: Save Method

In essence, the Save function:

- Takes a block object as input.
- Generates a unique file name (based on Block’s index and Timestamp).
- Creates a file for writing.
- Converts the block's data to JSON format.
- Writes the JSON data to the file.

Like the Save function, a **Load** Function has been created, responsible for the loading of the already existing (and saved blocks) to the chain, at application’s launch.

3.3.5 Examples and Data Filtering

In this Section, the total emissions from the batches of Arkoma (No.19) and Illinois (No. 16) will be entered into the blockchain, utilizing the methods mentioned above.

The emissions data have been collected from the update of the **“Inventory of U.S Greenhouse Gas Emissions and Sinks”** [1] that incorporates additional basin-level data.

In total there are 16 different processes (transactions) to be submitted for each batch. For both batches there is a total of 32 processes.

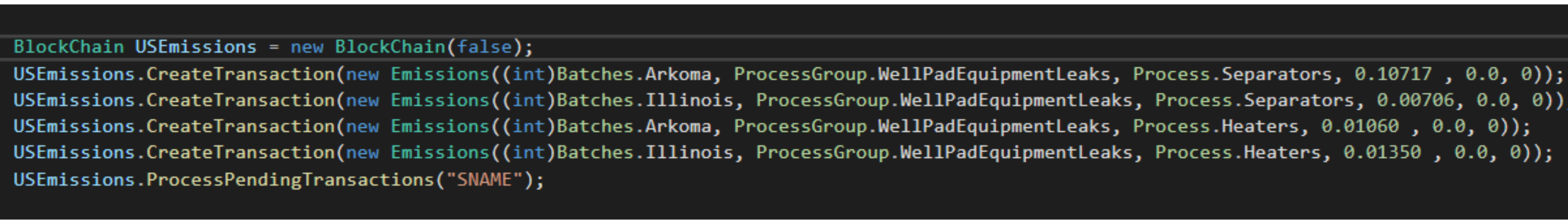
It has been decided that these processes be put in 8 different blocks, each of which containing 4 transactions. The order of transactions doesn’t matter in the result.

The total number of Blocks in the chain is 9. The 8 mentioned above, and the Genesis Block.

The data that have been used belong to Year 2021.

Process [No.]	**Process Group [No.]**		**CH_4 [kt]**		**CO_2 [kt]**	
	Arkoma	Illinois	Arkoma	Illinois	Arkoma	Illinois
Separators [0]	Well Pad Equipment Leaks [1]		0.10717	0.00706	0.00000	0.00000
Heaters [1]	Well Pad Equipment Leaks [1]		0.01060	0.01350	0.00000	0.00000
Dehydrators [2]	Well Pad Equipment Leaks [1]		0.10523	0.00395	0.00000	0.00000
Meters Piping [3]	Well Pad Equipment Leaks [1]		1.09350	0.10351	0.00000	0.00000
Compressors [4]	Well Pad Equipment Leaks [1]		3.50396	0.21441	0.00000	0.00000
High Bleed [5]	Pneumatic Controllers [0]		7.12170	0.15439	0.00000	0.00000
Low Bleed [6]	Pneumatic Controllers [0]		0.03413	0.10774	0.00000	0.00000
Intermittent Bleed [7]	Pneumatic Controllers [0]		12.46528	2.75915	0.00000	0.00000
Large Tanks with VRU [8]	Tanks [3]		0.00000	0.00097	0.00000	0.00197
Large Tanks without Control [9]	Tanks [3]		0.06622	0.01132	0.00834	0.00295
Small Tanks without Flares [10]	Tanks [3]		4.20758	0.04326	1.83384	0.02138
Malfunctioning Separator Dump Valves [11]	Tanks [3]		0.00000	0.00050	0.00000	0.00002
Large Tanks with Flares [12]	Tanks [3]		0.00000	0.00154	0.00000	2.32616
Small Tanks with Flares [13]	Tanks [3]		0.00000	0.00020	0.00000	0.03348
Liquids Unloading with Plunger Lifts [14]	Liquids Unloading [4]		7.12752	0.27757	0.46817	0.00000
Liquids Unloading without Plunger Lifts [15]	Liquids Unloading [4]		2.73856	0.47853	0.16057	0.00000

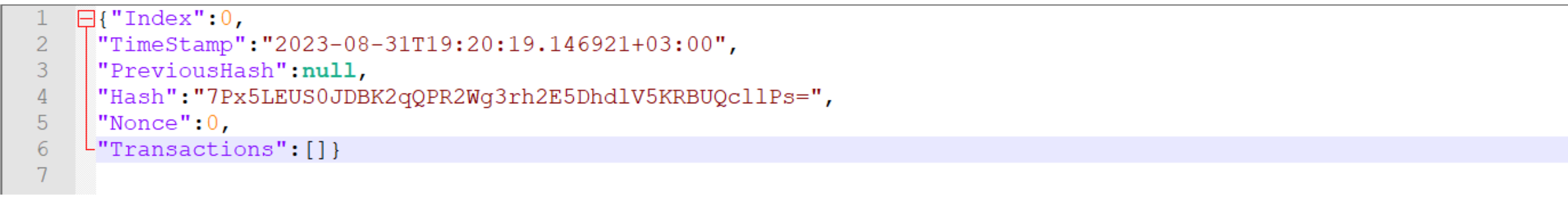
The snippet displayed in figure 3-23 initiates a new Chain called **"USEmissions"** and adds the first Block that contains 4 transactions. These transactions concern Heater and Separators emissions for both the Arkoma and Illinois basin:



```
BlockChain USEmissions = new BlockChain(false);
USEmissions.CreateTransaction(new Emissions((int)Batches.Arkoma, ProcessGroup.WellPadEquipmentLeaks, Process.Separators, 0.10717 , 0.0, 0));
USEmissions.CreateTransaction(new Emissions((int)Batches.Illinois, ProcessGroup.WellPadEquipmentLeaks, Process.Separators, 0.00706, 0.0, 0))
USEmissions.CreateTransaction(new Emissions((int)Batches.Arkoma, ProcessGroup.WellPadEquipmentLeaks, Process.Heaters, 0.01060 , 0.0, 0));
USEmissions.CreateTransaction(new Emissions((int)Batches.Illinois, ProcessGroup.WellPadEquipmentLeaks, Process.Heaters, 0.01350 , 0.0, 0));
USEmissions.ProcessPendingTransactions("SNAME");
```

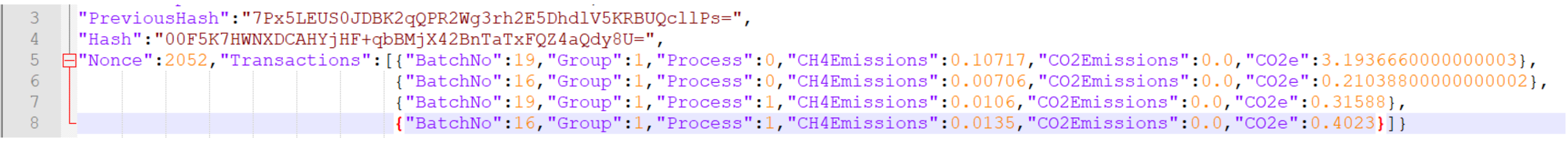
Figure 3-23: Snippet of 1st Block

The result is the creation of the 2 Blocks. The Genesis Block (Block 0), since the chain was just initiated, and the Block described above (Block 1).



```
{"Index":0,
"TimeStamp":"2023-08-31T19:20:19.146921+03:00",
"PreviousHash":null,
"Hash":"7Px5LEUS0JDBK2qQPR2Wg3rh2E5DhdlV5KRBUQcllPs=",
"Nonce":0,
"Transactions":[]}
```

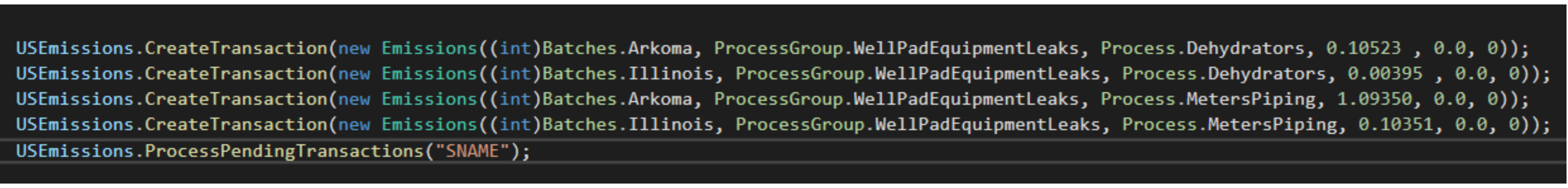
Figure 3-24: Block 0: Genesis Block



```
"PreviousHash":"7Px5LEUS0JDBK2qQPR2Wg3rh2E5DhdlV5KRBUQcllPs=",
"Hash":"00F5K7HWNXDCAHYjHF+qbBMjX42BnTaTxFQZ4aQdy8U=",
"Nonce":2052,"Transactions":[{"BatchNo":19,"Group":1,"Process":0,"CH4Emissions":0.10717,"CO2Emissions":0.0,"CO2e":3.1936660000000003},
                             {"BatchNo":16,"Group":1,"Process":0,"CH4Emissions":0.00706,"CO2Emissions":0.0,"CO2e":0.21038800000000002},
                             {"BatchNo":19,"Group":1,"Process":1,"CH4Emissions":0.0106,"CO2Emissions":0.0,"CO2e":0.31588},
                             {"BatchNo":16,"Group":1,"Process":1,"CH4Emissions":0.0135,"CO2Emissions":0.0,"CO2e":0.4023}]}
```

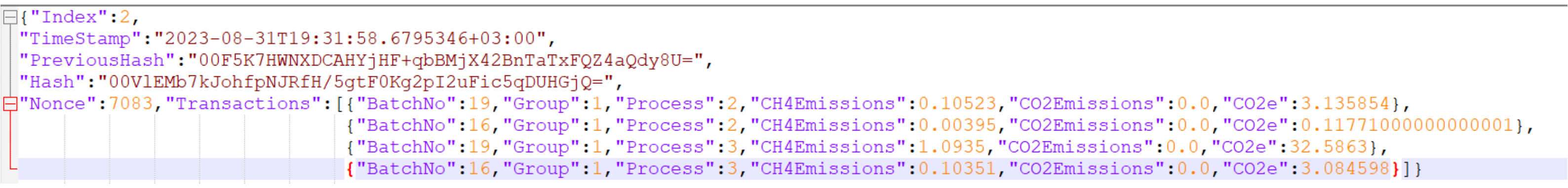
Figure 3-25: Block 1: Heaters and Separators Block

The 2nd Block consists of the Emissions from Dehydrators and Meters/Piping, and is created as follows:



```
USEmissions.CreateTransaction(new Emissions((int)Batches.Arkoma, ProcessGroup.WellPadEquipmentLeaks, Process.Dehydrators, 0.10523 , 0.0, 0));
USEmissions.CreateTransaction(new Emissions((int)Batches.Illinois, ProcessGroup.WellPadEquipmentLeaks, Process.Dehydrators, 0.00395 , 0.0, 0));
USEmissions.CreateTransaction(new Emissions((int)Batches.Arkoma, ProcessGroup.WellPadEquipmentLeaks, Process.MetersPiping, 1.09350, 0.0, 0));
USEmissions.CreateTransaction(new Emissions((int)Batches.Illinois, ProcessGroup.WellPadEquipmentLeaks, Process.MetersPiping, 0.10351, 0.0, 0));
USEmissions.ProcessPendingTransactions("SNAME");
```

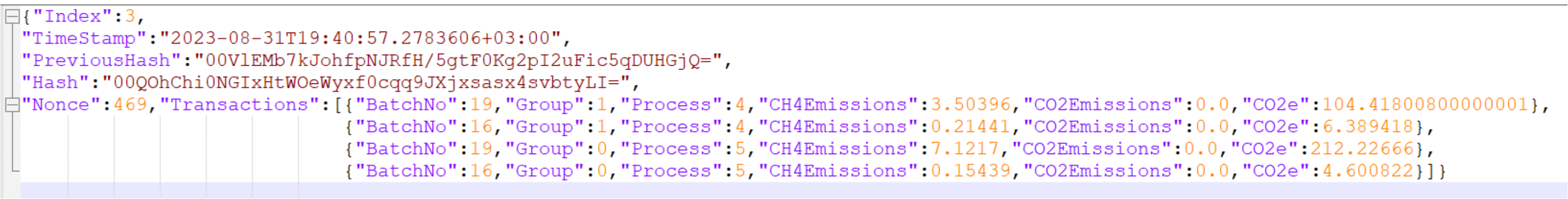
Figure 3-26: Snippet of 2nd Block



```
{"Index":2,
"TimeStamp":"2023-08-31T19:31:58.6795346+03:00",
"PreviousHash":"00F5K7HWNXDCAHYjHF+qbBMjX42BnTaTxFQZ4aQdy8U=",
"Hash":"00VlEMb7kJohfpNJRfH/5gtF0Kg2pI2uFic5qDUHGjQ=",
"Nonce":7083,"Transactions":[{"BatchNo":19,"Group":1,"Process":2,"CH4Emissions":0.10523,"CO2Emissions":0.0,"CO2e":3.135854},
                             {"BatchNo":16,"Group":1,"Process":2,"CH4Emissions":0.00395,"CO2Emissions":0.0,"CO2e":0.11771000000000001},
                             {"BatchNo":19,"Group":1,"Process":3,"CH4Emissions":1.0935,"CO2Emissions":0.0,"CO2e":32.5863},
                             {"BatchNo":16,"Group":1,"Process":3,"CH4Emissions":0.10351,"CO2Emissions":0.0,"CO2e":3.084598}]}
```

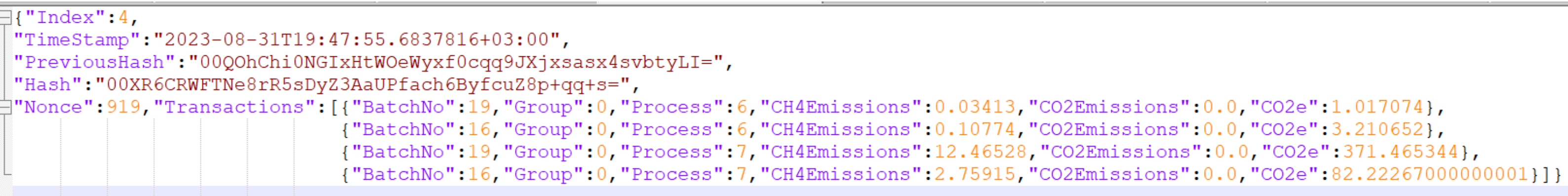
Figure 3-27: Block 2: Dehydrators and Meters/Piping

Similarly, the next 7 blocks have been created:



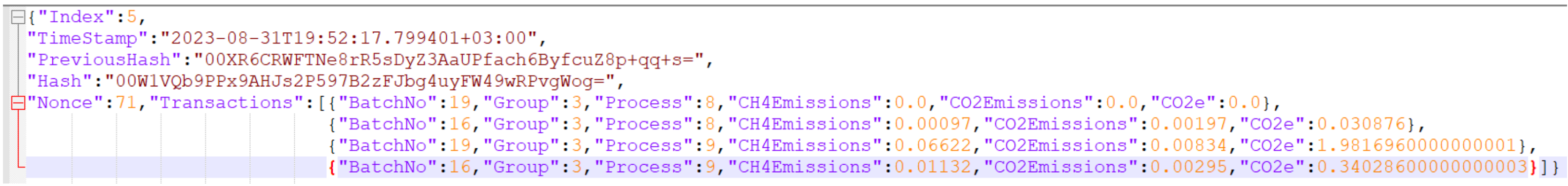
```
{"Index":3,
"TimeStamp":"2023-08-31T19:40:57.2783606+03:00",
"PreviousHash":"00VlEMb7kJohfpNJRfH/5gtF0Kg2pI2uFic5qDUHGjQ=",
"Hash":"00QOhChi0NGIxHtWOeWyxf0cqq9JXjxsasx4svbtyLI=",
"Nonce":469,"Transactions":[{"BatchNo":19,"Group":1,"Process":4,"CH4Emissions":3.50396,"CO2Emissions":0.0,"CO2e":104.41800800000001},
                            {"BatchNo":16,"Group":1,"Process":4,"CH4Emissions":0.21441,"CO2Emissions":0.0,"CO2e":6.389418},
                            {"BatchNo":19,"Group":0,"Process":5,"CH4Emissions":7.1217,"CO2Emissions":0.0,"CO2e":212.22666},
                            {"BatchNo":16,"Group":0,"Process":5,"CH4Emissions":0.15439,"CO2Emissions":0.0,"CO2e":4.600822}]}
```

Figure 3-28: Block 3 Compressors and High Bleed Pneumatic Controllers



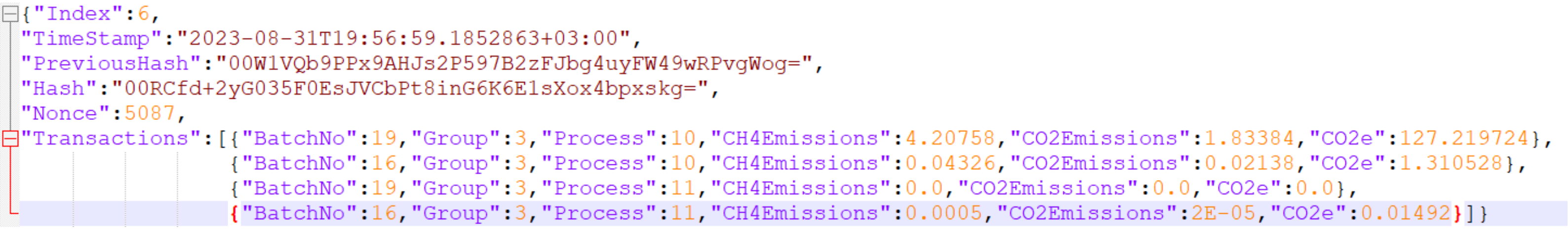
```
{"Index":4,
"TimeStamp":"2023-08-31T19:47:55.6837816+03:00",
"PreviousHash":"00QOhChi0NGIxHtWOeWyxf0cqq9JXjxsasx4svbtyLI=",
"Hash":"00XR6CRWFTNe8rR5sDyZ3AaUPfach6ByfcuZ8p+qq+s=",
"Nonce":919,"Transactions":[{"BatchNo":19,"Group":0,"Process":6,"CH4Emissions":0.03413,"CO2Emissions":0.0,"CO2e":1.017074},
                            {"BatchNo":16,"Group":0,"Process":6,"CH4Emissions":0.10774,"CO2Emissions":0.0,"CO2e":3.210652},
                            {"BatchNo":19,"Group":0,"Process":7,"CH4Emissions":12.46528,"CO2Emissions":0.0,"CO2e":371.465344},
                            {"BatchNo":16,"Group":0,"Process":7,"CH4Emissions":2.75915,"CO2Emissions":0.0,"CO2e":82.22267000000001}]}
```

Figure 3-29: Block 4 Low and Intermittent Bleed Pneumatic Controllers



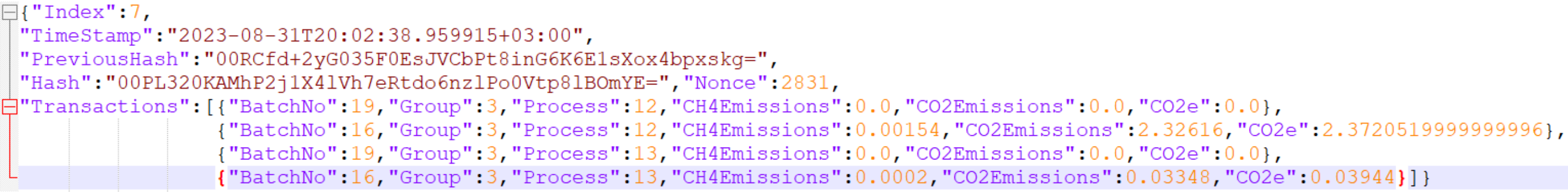
```
{"Index":5,
"TimeStamp":"2023-08-31T19:52:17.799401+03:00",
"PreviousHash":"00XR6CRWFTNe8rR5sDyZ3AaUPfach6ByfcuZ8p+qq+s=",
"Hash":"00W1VQb9PPx9AHJs2P597B2zFJbg4uyFW49wRPvgWog=",
"Nonce":71,"Transactions":[{"BatchNo":19,"Group":3,"Process":8,"CH4Emissions":0.0,"CO2Emissions":0.0,"CO2e":0.0},
                           {"BatchNo":16,"Group":3,"Process":8,"CH4Emissions":0.00097,"CO2Emissions":0.00197,"CO2e":0.030876},
                           {"BatchNo":19,"Group":3,"Process":9,"CH4Emissions":0.06622,"CO2Emissions":0.00834,"CO2e":1.9816960000000001},
                           {"BatchNo":16,"Group":3,"Process":9,"CH4Emissions":0.01132,"CO2Emissions":0.00295,"CO2e":0.34028600000000003}]}
```

Figure 3-30: Block 5: Large Tanks w/ VRU and Large Tanks w/o Control



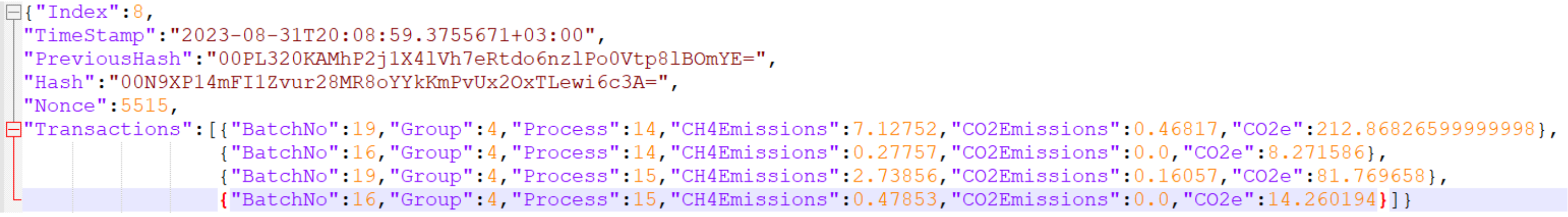
```
{"Index":6,
"TimeStamp":"2023-08-31T19:56:59.1852863+03:00",
"PreviousHash":"00W1VQb9PPx9AHJs2P597B2zFJbg4uyFW49wRPvgWog=",
"Hash":"00RCfd+2yG035F0EsJVCbPt8inG6K6E1sXox4bpxskg=",
"Nonce":5087,
"Transactions":[{"BatchNo":19,"Group":3,"Process":10,"CH4Emissions":4.20758,"CO2Emissions":1.83384,"CO2e":127.219724},
                {"BatchNo":16,"Group":3,"Process":10,"CH4Emissions":0.04326,"CO2Emissions":0.02138,"CO2e":1.310528},
                {"BatchNo":19,"Group":3,"Process":11,"CH4Emissions":0.0,"CO2Emissions":0.0,"CO2e":0.0},
                {"BatchNo":16,"Group":3,"Process":11,"CH4Emissions":0.0005,"CO2Emissions":2E-05,"CO2e":0.01492}]}
```

Figure 3-31: Block 6: Small Tank w/o Flares and Malfunctioning Separator Dump Valves



```
{"Index":7,
"TimeStamp":"2023-08-31T20:02:38.959915+03:00",
"PreviousHash":"00RCfd+2yG035F0EsJVCbPt8inG6K6E1sXox4bpxskg=",
"Hash":"00PL320KAMhP2j1X4lVh7eRtdo6nzlPo0Vtp8lBOmYE=","Nonce":2831,
"Transactions":[{"BatchNo":19,"Group":3,"Process":12,"CH4Emissions":0.0,"CO2Emissions":0.0,"CO2e":0.0},
                {"BatchNo":16,"Group":3,"Process":12,"CH4Emissions":0.00154,"CO2Emissions":2.32616,"CO2e":2.3720519999999996},
                {"BatchNo":19,"Group":3,"Process":13,"CH4Emissions":0.0,"CO2Emissions":0.0,"CO2e":0.0},
                {"BatchNo":16,"Group":3,"Process":13,"CH4Emissions":0.0002,"CO2Emissions":0.03348,"CO2e":0.03944}]}
```

Figure 3-32: Block 7: Large Tanks w/ Flares and Small Tanks w/ Flares



```
{"Index":8,
"TimeStamp":"2023-08-31T20:08:59.3755671+03:00",
"PreviousHash":"00PL320KAMhP2j1X4lVh7eRtdo6nzlPo0Vtp8lBOmYE=",
"Hash":"00N9XP14mFI1Zvur28MR8oYYkKmPvUx2OxTLewi6c3A=",
"Nonce":5515,
"Transactions":[{"BatchNo":19,"Group":4,"Process":14,"CH4Emissions":7.12752,"CO2Emissions":0.46817,"CO2e":212.86826599999998},
                {"BatchNo":16,"Group":4,"Process":14,"CH4Emissions":0.27757,"CO2Emissions":0.0,"CO2e":8.271586},
                {"BatchNo":19,"Group":4,"Process":15,"CH4Emissions":2.73856,"CO2Emissions":0.16057,"CO2e":81.769658},
                {"BatchNo":16,"Group":4,"Process":15,"CH4Emissions":0.47853,"CO2Emissions":0.0,"CO2e":14.260194}]}
```

Figure 3-33: Block 8: Liquids Unloading with (and without) Plunger Lifts

The full Blockchain can be seen in Figures 3-34 and 3-35. The transactions have been hidden due to lack of space.

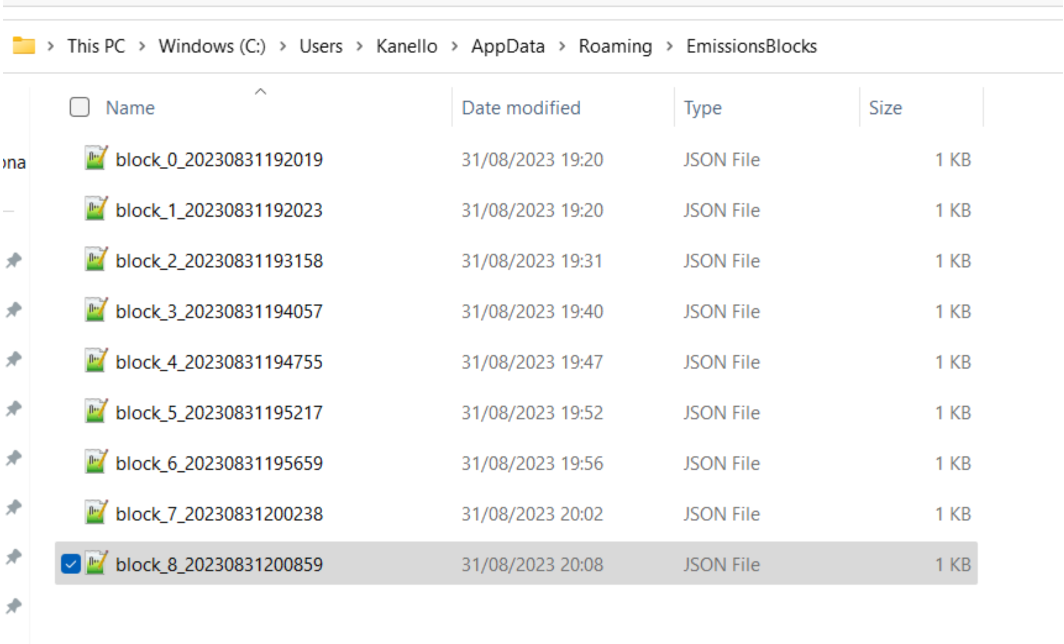
```
"Chain": [
  {
    "Index": 0,
    "TimeStamp": "2023-08-31T19:20:19",
    "PreviousHash": "",
    "Hash": "7Px5LEUS0JDBK2qQPR2Wg3rh2E5Dhd1V5KRBUQc1lPs=",
    "Nonce": 0,
    "Transactions": []
  },
  {
    "Index": 1,
    "TimeStamp": "2023-08-31T19:20:23",
    "PreviousHash": "7Px5LEUS0JDBK2qQPR2Wg3rh2E5Dhd1V5KRBUQc1lPs=",
    "Hash": "00F5K7HWNXDCAHYjHF+qbBMjX42BnTaTxFQZ4aQdy8U=",
    "Nonce": 2052,
    "Transactions": [
  },
  {
    "Index": 2,
    "TimeStamp": "2023-08-31T19:31:58",
    "PreviousHash": "00F5K7HWNXDCAHYjHF+qbBMjX42BnTaTxFQZ4aQdy8U=",
    "Hash": "00VlEMb7kJohfpNJRfH/5gtF0Kg2pI2uFic5qDUHGjQ=",
    "Nonce": 7083,
    "Transactions": [
  },
  {
    "Index": 3,
    "TimeStamp": "2023-08-31T19:40:57",
    "PreviousHash": "00VlEMb7kJohfpNJRfH/5gtF0Kg2pI2uFic5qDUHGjQ=",
    "Hash": "00QOhChi0NGIxHtWOeWyxf0cqq9JXjxsasx4svbtyLI=",
    "Nonce": 469,
    "Transactions": [
  },
  {
    "Index": 4,
    "TimeStamp": "2023-08-31T19:47:55",
    "PreviousHash": "00QOhChi0NGIxHtWOeWyxf0cqq9JXjxsasx4svbtyLI=",
    "Hash": "00XR6CRWFTNe8rR5sDyZ3AaUPfach6ByfcuZ8p+qq+s=",
    "Nonce": 919,
    "Transactions": [
```

Figure 3-34: Entire Blockchain 1st part

```
  },
  {
    "Index": 5,
    "TimeStamp": "2023-08-31T19:52:17",
    "PreviousHash": "00XR6CRWFTNe8rR5sDyZ3AaUPfach6ByfcuZ8p+qq+s=",
    "Hash": "00W1VQb9PPx9AHJs2P597B2zFJbg4uyFW49wRPvgWog=",
    "Nonce": 71,
    "Transactions": [
  },
  {
    "Index": 6,
    "TimeStamp": "2023-08-31T19:56:59",
    "PreviousHash": "00W1VQb9PPx9AHJs2P597B2zFJbg4uyFW49wRPvgWog=",
    "Hash": "00RCfd+2yG035F0EsJVCbPt8inG6K6E1sXox4bpxskg=",
    "Nonce": 5087,
    "Transactions": [
  },
  {
    "Index": 7,
    "TimeStamp": "2023-08-31T20:02:38",
    "PreviousHash": "00RCfd+2yG035F0EsJVCbPt8inG6K6E1sXox4bpxskg=",
    "Hash": "00PL320KAMhP2j1X41Vh7eRtdo6nzlPo0Vtp81BOmYE=",
    "Nonce": 2831,
    "Transactions": [
  },
  {
    "Index": 8,
    "TimeStamp": "2023-08-31T20:08:59",
    "PreviousHash": "00PL320KAMhP2j1X41Vh7eRtdo6nzlPo0Vtp81BOmYE=",
    "Hash": "00N9XP14mFI1Zvur28MR8oYYkKmPvUx2OxTLewi6c3A=",
    "Nonce": 5515,
    "Transactions": [
  }
],
"Difficulty": 2
}
```

Figure 3-35: Entire Blockchain 2nd part

These Blocks have also been saved in EmissionsBlocks folder as shown in Figure 3-36:

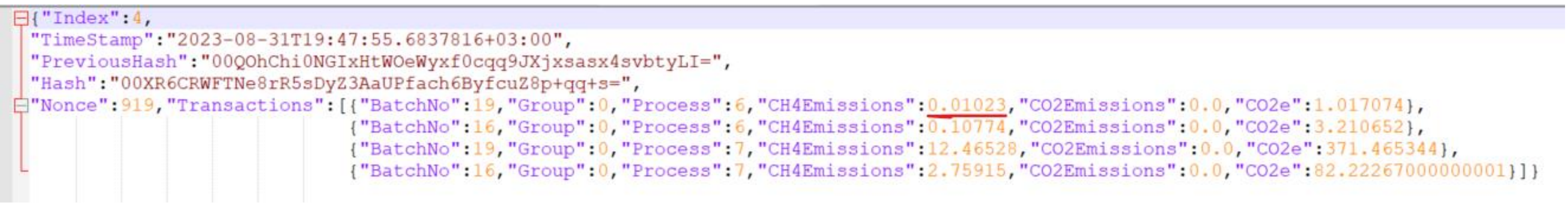


☐ Name	Date modified	Type	Size
block_0_20230831192019	31/08/2023 19:20	JSON File	1 KB
block_1_20230831192023	31/08/2023 19:20	JSON File	1 KB
block_2_20230831193158	31/08/2023 19:31	JSON File	1 KB
block_3_20230831194057	31/08/2023 19:40	JSON File	1 KB
block_4_20230831194755	31/08/2023 19:47	JSON File	1 KB
block_5_20230831195217	31/08/2023 19:52	JSON File	1 KB
block_6_20230831195659	31/08/2023 19:56	JSON File	1 KB
block_7_20230831200238	31/08/2023 20:02	JSON File	1 KB
☑ block_8_20230831200859	31/08/2023 20:08	JSON File	1 KB

Figure 3-36: List of all the Blocks in .JSON files

Validation: In order to see the operation of the **validation** method into action, the 4th block has been tampered.

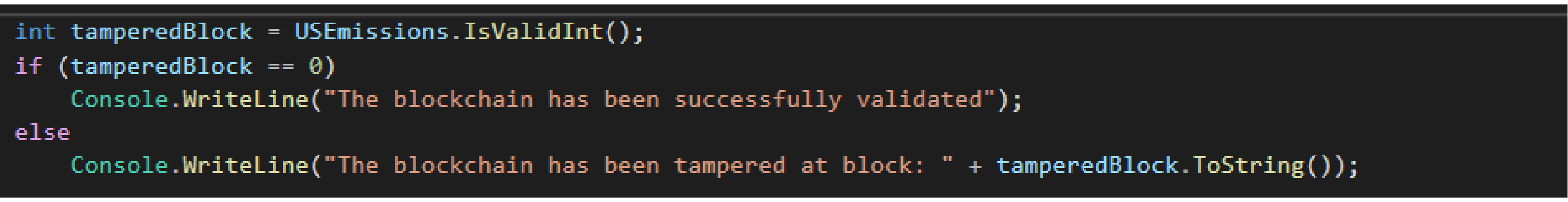
The CH_4 emission from the Low Bleed Pneumatic Controllers of Arkoma Basin has been set from “0.03413” to “0.01023”.



```
{"Index":4,
"TimeStamp":"2023-08-31T19:47:55.6837816+03:00",
"PreviousHash":"00QOhChi0NGIxHtWOeWyxf0cqq9JXjxsasx4svbtyLI=",
"Hash":"00XR6CRWFTNe8rR5sDyZ3AaUPfach6ByfcuZ8p+qq+s=",
"Nonce":919,"Transactions":[{"BatchNo":19,"Group":0,"Process":6,"CH4Emissions":0.01023,"CO2Emissions":0.0,"CO2e":1.017074},
                            {"BatchNo":16,"Group":0,"Process":6,"CH4Emissions":0.10774,"CO2Emissions":0.0,"CO2e":3.210652},
                            {"BatchNo":19,"Group":0,"Process":7,"CH4Emissions":12.46528,"CO2Emissions":0.0,"CO2e":371.465344},
                            {"BatchNo":16,"Group":0,"Process":7,"CH4Emissions":2.75915,"CO2Emissions":0.0,"CO2e":82.22267000000001}]}
```

Figure 3-37: Tampered 4th Block

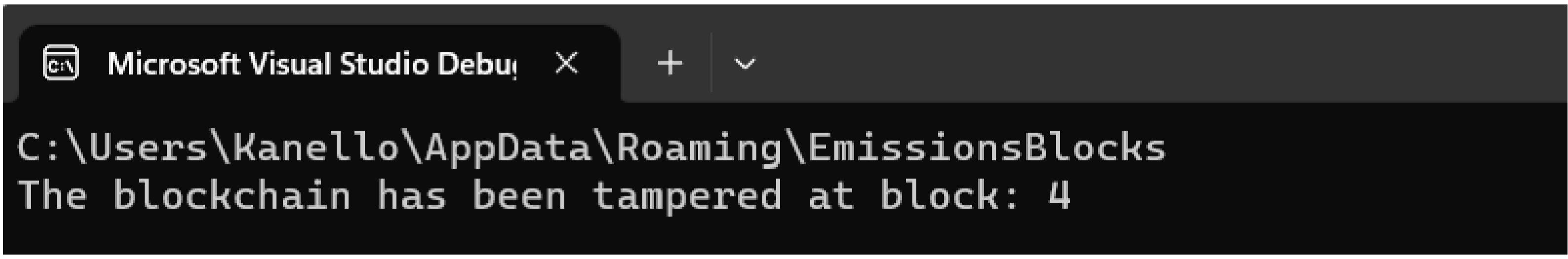
The validation is called as follows:



```
int tamperedBlock = USEmissions.IsValidInt();
if (tamperedBlock == 0)
    Console.WriteLine("The blockchain has been successfully validated");
else
    Console.WriteLine("The blockchain has been tampered at block: " + tamperedBlock.ToString());
```

Figure 3-38: Validation Method Call

The result of the method, clearly displaying the number of the tampered block, is presented in Figure 3-39:



```
C:\Users\Kanello\AppData\Roaming\EmissionsBlocks
The blockchain has been tampered at block: 4
```

Figure 3-39: Result from Validation

Data Filtering:

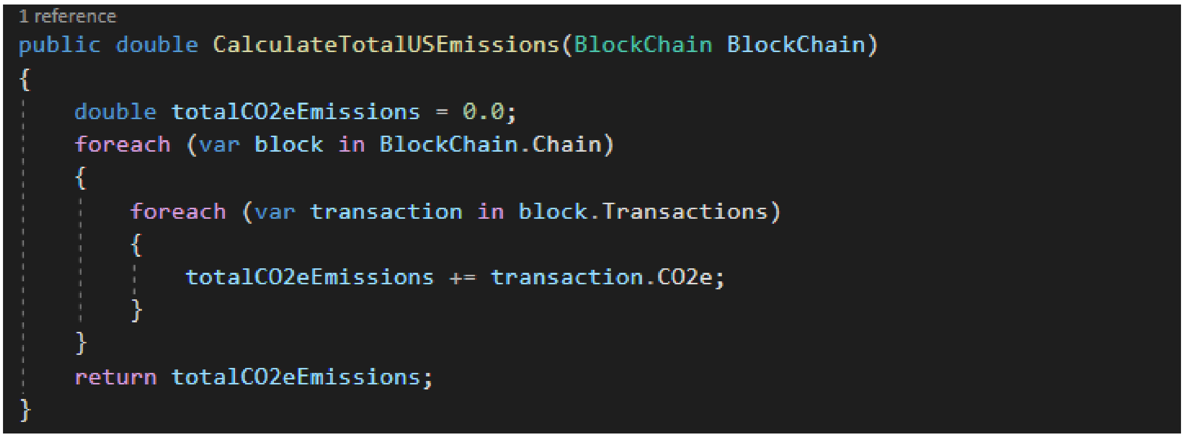
The users of the US Emissions blockchain have the ability to filter and explore the blockchain by focusing on specific subsets of data.

For the purpose of this application, 4 different filtering functions have been created:

- Calculation of total **US Emissions.**
- Calculation of total emissions per **Basin.**
- Calculation of total US emissions per **Process.**
- Calculation of total US emissions per **Process Group.**
- Calculation of Emissions from **Custom Criteria**.

A more detailed filtering mechanism, that considers more parameters, could be created. For the time being, this application is adequately served by the filtering functions described above.

1) Calculation of total US Emissions.

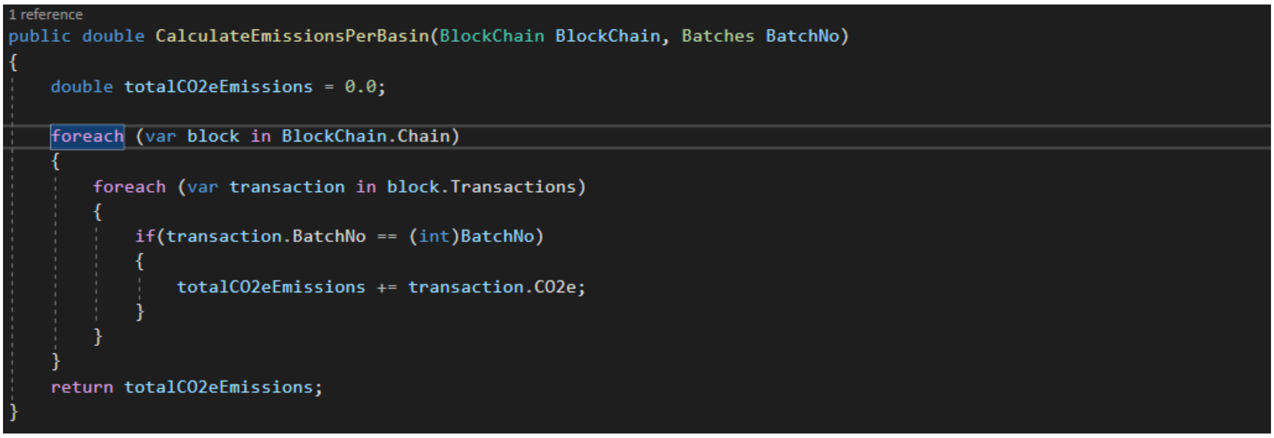


```
public double CalculateTotalUSEmissions(BlockChain BlockChain)
{
    double totalCO2eEmissions = 0.0;
    foreach (var block in BlockChain.Chain)
    {
        foreach (var transaction in block.Transactions)
        {
            totalCO2eEmissions += transaction.CO2e;
        }
    }
    return totalCO2eEmissions;
}
```

Figure 3-40: Total US Emissions Calculation

This method iterates through each block and its associated transactions in the blockchain. For each transaction, it adds the $CO2_e$ emissions to a running total. Finally, it returns the overall sum of $CO2_e$ emissions found in all the transactions across all blocks in the blockchain. The total result for this example is: **1279.07657** [kt] per year.

2) Calculation of total emissions per **Basin.**



```
1 reference
public double CalculateEmissionsPerBasin(BlockChain BlockChain, Batches BatchNo)
{
    double totalCO2eEmissions = 0.0;

    foreach (var block in BlockChain.Chain)
    {
        foreach (var transaction in block.Transactions)
        {
            if(transaction.BatchNo == (int)BatchNo)
            {
                totalCO2eEmissions += transaction.CO2e;
            }
        }
    }
    return totalCO2eEmissions;
}
```

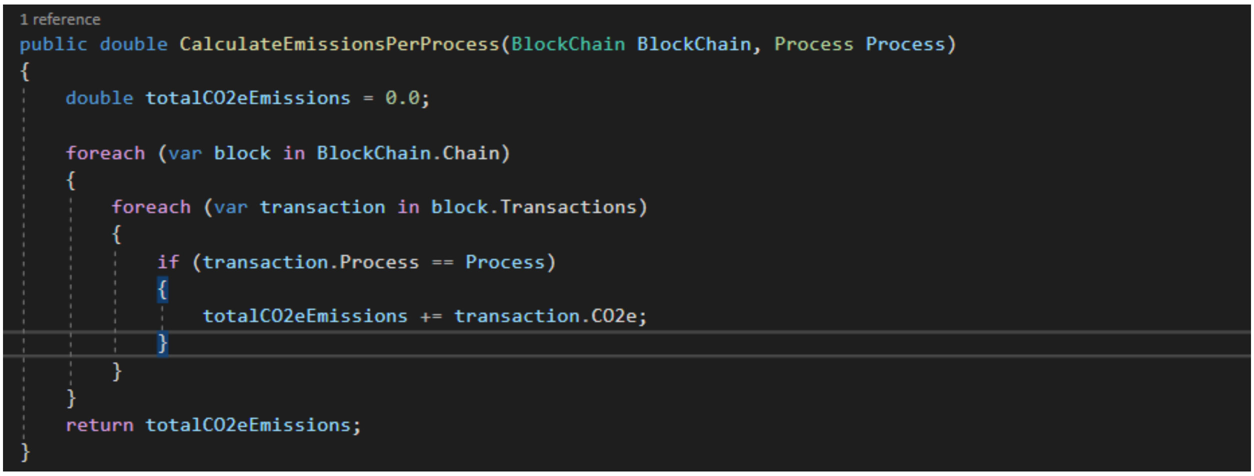
Figure 3-41: Total Emissions per Basin

Much like the CalculateTotalUSEmissions() function, this method also goes through each block. However, when the user utilizes this method, they provide the basin as a parameter to narrow down the search.

This method introduces an extra filtering step where it verifies whether the Batch Number aligns with the user's specified value. The result of this function for the two Basins is:

- **Arkoma**: 1152.19813 [kt]
- **Illinois**: 126.87844 [kt]

3) Calculation of total US emissions per **Process.**

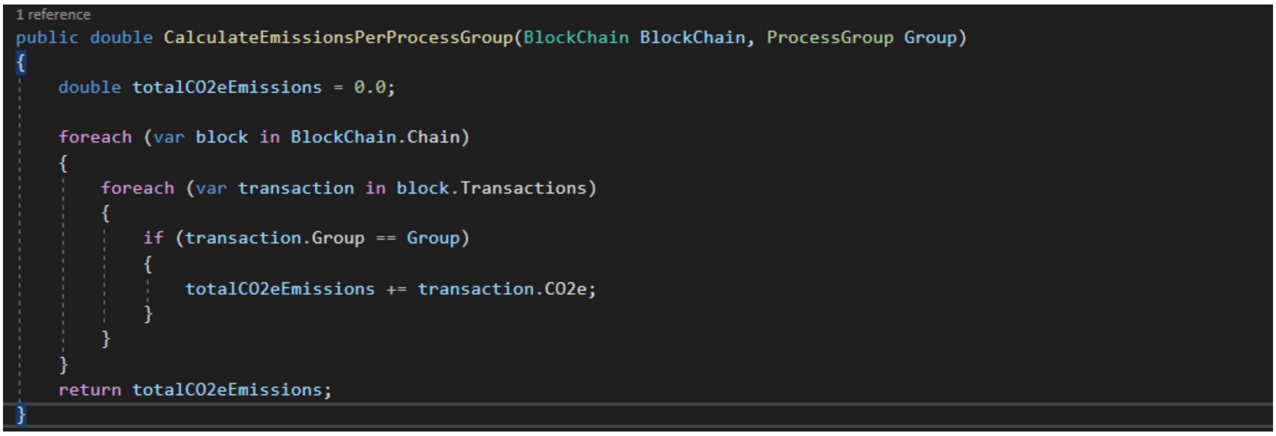


```
1 reference
public double CalculateEmissionsPerProcess(BlockChain BlockChain, Process Process)
{
    double totalCO2eEmissions = 0.0;

    foreach (var block in BlockChain.Chain)
    {
        foreach (var transaction in block.Transactions)
        {
            if (transaction.Process == Process)
            {
                totalCO2eEmissions += transaction.CO2e;
            }
        }
    }
    return totalCO2eEmissions;
}
```

Figure 3-42: Total Emissions per Process

When the user utilizes this method, they provide the Process as a parameter to narrow down the search. In this case, the selected process was the “Compressors”. The result of this function was: **110.8074** [kt]

4) Calculation of total US emissions per **Process Group.**



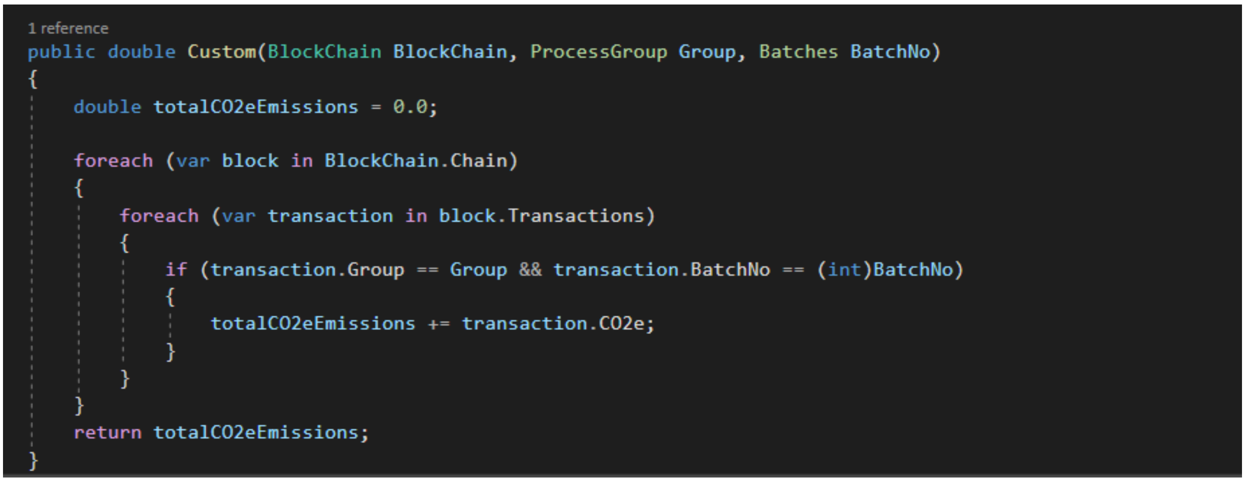
```
1 reference
public double CalculateEmissionsPerProcessGroup(BlockChain BlockChain, ProcessGroup Group)
{
    double totalCO2eEmissions = 0.0;

    foreach (var block in BlockChain.Chain)
    {
        foreach (var transaction in block.Transactions)
        {
            if (transaction.Group == Group)
            {
                totalCO2eEmissions += transaction.CO2e;
            }
        }
    }
    return totalCO2eEmissions;
}
```

Figure 3-43: Total Emissions per Process Group

When the user utilizes this method, they provide the Process Group as a parameter to narrow down the search. In this case, the selected process Group was "Well Pad Equipment Leaks". The result of this function was: **153.85412** [kt]

5) Calculation of Emissions from **Custom Criteria**.

The user can perform many combinations of the above search criteria. For example, the user can filter for specific Basin and Process Group:



```
1 reference
public double Custom(BlockChain BlockChain, ProcessGroup Group, Batches BatchNo)
{
    double totalCO2eEmissions = 0.0;

    foreach (var block in BlockChain.Chain)
    {
        foreach (var transaction in block.Transactions)
        {
            if (transaction.Group == Group && transaction.BatchNo == (int)BatchNo)
            {
                totalCO2eEmissions += transaction.CO2e;
            }
        }
    }
    return totalCO2eEmissions;
}
```

Figure 3-44: Emissions from Custom Filtering Criteria

The selected criteria for the custom search were:

- **Basin**: Arkoma (Batch No. 19)
- **Process Group**: Well Pad Equipment Leaks (Process Group No. 1)

The result was: **143.64971** [kt]

Conclusions

This research has proven that the development of a Blockchain-enabled emissions management system in the natural gas supply chain is feasible. The steps to reach this conclusion include:

1. A thorough research on the natural gas supply chain network aiming at identifying all possible sources of emissions.
2. The mapping of the emissions using a multi-tier architecture, which clearly states the stage of production that each emission refers to.
3. The development of an application that is governed by the principles of Blockchain Technology and efficiently stores and retrieves emissions data from the Blockchain.
4. Performing a case study wherein annual emissions data linked to the operations of natural gas plants in US basins, as reported by the EPA, were incorporated into the application.

This research in combination with the developed application provides the framework upon which further development will be based.

Therefore, certain suggestions for future research and development are proposed:

- *Emissions Mapping Expansion:* The existing mapping should be expanded to contain the plethora of emissions presented in EPA's report.
- *Deployment in a public and decentralized network:* The current pseudo-blockchain application operates locally and it is not distributed. It is proposed that future researchers deploy this application in a public network where different nodes interact.
- *Data Collection through IOT sensors:* The use of Internet of Thing (IoT) for data collection has penetrated the industry in recent years. The real-time submission of emissions that have been collected by IoT devices would improve efficiency and transparency as it eliminates human error.
- *Automation of bureaucratic procedures:* By the development of smart contracts many time-consuming bureaucratic procedures can be automated. These procedures include:
  - Manual audits and certifications on emissions reduction.
  - Mandatory reports for meeting regulatory compliance.
  - Complex transactions for emissions trading or carbon credits which traditionally involve intermediaries.

Chapter 4 : References

[1] European Parliament: What is carbon neutrality and how can it be achieved by 2050?

https://www.europarl.europa.eu/news/en/headlines/society/20190926STO62270/what-is-carbon-neutrality-and-how-can-it-be-achieved-by-2050?&at_campaign=20234-Green&at_medium=Google_Ads&at_platform=Search&at_creation=RSA&at_goal=TR_G&at_audience=carbon%202050&.

[2] World Resources Institute: What Does "Net-Zero Emissions" Mean?

https://www.wri.org/insights/net-zero-ghg-emissions-questions-answered#:~:text=Net%2Dzero%20emissions%2C%20or%20%E2%80%9C,process%20known%20as%20carbon%20removal..

[3] Rudiger Hahn, Daniel Reimsbach, Frank Schiemann. Organizations, Climate Change, and Transparency: Reviewing the Literature on Carbon Disclosure, 2015.

[4] European Commission:

https://digital-strategy.ec.europa.eu/en/policies/blockchain-climate-action

[5] Cem Dilmegani. Blockchain in Supply Chain: Benefits & Top Use Cases in 2023, 2023.

[6] Enbridge: Chemical Composition of Natural Gas

https://www.enbridgegas.com/en/about-enbridge-gas/learn-about-natural-gas.

[7] American Lung Association: Why Everyone Should Care About Methane Gas Pollution?

https://www.lung.org/blog/methane-gas-pollution#:~:text=Though%20it%20breaks%20down%20more,change%20since%20pre%2Dindustrial%20times..

[8] U.S. Energy Information Administration: Natural gas explained.

https://www.eia.gov/energyexplained/natural-gas/natural-gas-and-the-environment.php

[9] National Energy Technology Laboratory (NETL), Timothy J. Skone, James Littlefield, Dr. Joe Marriott, Greg Cooney, Matt Jamieson, Jeremie Hakian, and Greg Schivley, Booz Allen Hamilton. Life Cycle Analysis of Natural Gas Extraction and Power Generation, 2014

[10] Boyun Guo PhD, Xinghui Liu PhD, Xuehao Tan PhD. Petroleum Production Engineering 2017, Pages 503-511.

[11] Sigma Thermal: Gas Processing

https://www.sigmathermal.com/industries/gas-processing-process-heating/#:~:text=The%20Role%20of%20Heaters%20in,function%20is%20the%20immersion%20heater..

[12] James Speight. Shale Oil and Gas Production Processes, 2020, Pages 451-518.

[13] Cimmaron: Glycol Dehydration and Emission Controls

https://cimarron.com/glycol-dehydration-process-and-emission-controls/

[14] Saeid Mokhatab, William A. Poe, John Y. Mak. Handbook of Natural Gas Transmission and Processing (Fourth Edition), 2019, Pages 433-461.

[15] Environmental Protection Agency: Basic Information of Air Emissions Factors.

https://www.epa.gov/air-emissions-factors-and-quantification/basic-information-air-emissions-factors-and-quantification#:~:text=An%20emissions%20factor%20is%20a,the%20release%20of%20that%20pollutant..

[16] Penn State University: Natural Gas Processing.

https://www.e-education.psu.edu/fsc432/content/natural-gas-processing

[17] Natural Gas Org: Processing Natural Gas

http://naturalgas.org/naturalgas/processing-ng/#oil

[18] Environmental Protection Agency: Natural Gas Processing.

https://www.epa.gov/sites/default/files/2020-09/documents/5.3_natural_gas_processing.pdf

[19] Satyam Mishra, Mercury treatment options for natural gas plants.

https://cdn.digitalrefining.com/data/articles/file/992921612.pdf

[20] Linde Engineering: Nitrogen Rejection Units (NRUs)

https://www.linde-engineering.com/en/process-plants/lng-and-natural-gas-processing-plants/nitrogen-rejection/index.html

[21] J.C. Kuo, K.H.Wang, Chris Chen. Journal of Natural Gas Science and Engineering, Volume 7, July 2012, Pages 52-59.

[22] Saeid Mokhatab, William A. Poe, John Y. Mak. Handbook of Natural Gas Transmission and Processing (Fourth Edition), 2019, Pages 433-461.

[23] Saeid Mokhatab, Handbook of Liquefied Natural Gas 2014, Pages 107-145

[24] Department of Energy and Environmental Protection Public Utilities Regulatory Authority: What is LNG?

https://portal.ct.gov/PURA/Gas-Pipeline-Safety/What-is-LNG.#:~:text=LNG%20is%20an%20abbreviation%20for,the%20volume%20of%20natural%20gas..

[25] U.S. Energy Information Administration: Natural gas explained.

https://www.eia.gov/energyexplained/natural-gas/delivery-and-storage.php#:~:text=Natural%20gas%20storage%20during%20periods,tanks%20above%20or%20below%20ground..

[26] Environmental Protection Agency

https://www.epa.gov/sites/default/files/2016-06/documents/ll_final_vap.pdf

[27] Haamavaran Energy Pars: City Gates Stations Natural Gas.

http://www.hep-co.com/city-gates-stations-natural-gas/

[28] Enerdynamics: Regulation Stations

https://www.energyknowledgebase.com/topics/regulation-station.asp#:~:text=A%20gas%20regulation%20station%20is,section%20of%20the%20delivery%20system.

[29] Environmental Protection Agency: Natural Gas and Petroleum Systems in the GHG Inventory: Additional Information on the 1990-2021 GHG Inventory (published April 2023).

https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems-ghg-inventory-additional-information-1990-2021-ghg

[30] Ravindhar Vadapalli. BLOCKCHAIN FUNDAMENTALS TEXTBOOK Blockchain Fundamentals, 2023.

[31] Investopedia, Adam Hayes: Learn what these digital public ledgers are capable of.

https://www.investopedia.com/terms/b/blockchain.asp#:~:text=In%20Bitcoin's%20case%2C%20blockchain%20is,the%20data%20entered%20is%20irreversible.

[32] Synopsys: Blockchain.

https://www.synopsys.com/glossary/what-is-blockchain.html

[33] O'REILLY: The Blockchain.

https://www.oreilly.com/library/view/mastering-bitcoin/9781491902639/ch07.html#:~:text=Structure%20of%20a%20Block,the%20bulk%20of%20its%20size..

[34] Cleartax, Sujaini Biswas: What is consensus in Blockchain?

https://cleartax.in/s/consensus-in-blockchain.

[35] Blockworks, John Lee Quigley, John Gilbert: What Is Proof-of-work (PoW)? All You Need to Know.

https://blockworks.co/news/what-is-proof-of-work

[36] Investopedia, Luke Conway: What Is Bitcoin Halving? Definition, How It Works, Why It Matters.

https://www.investopedia.com/bitcoin-halving-4843769#:~:text=As%20of%202023%2C%20network%20participants,reward%20will%20fall%20to%203.125..

[37] Business Insider Simon Chandler: Proof of Work.

https://www.businessinsider.com/personal-finance/proof-of-work

[38] 101 Blockchains: Introduction to Permissioned Blockchains.

https://101blockchains.com/permissioned-blockchain/

[39] Oracle: Permissioned Blockchain.

https://developer.oracle.com/learn/technical-articles/permissioned-blockchain#:~:text=Permissioned%20blockchains%20are%20blockchains%20that,accessed%20by%20users%20with%20permissions..

[40] Investopedia, James Frankenfield: What Are Smart Contracts on the Blockchain and How They Work.

https://www.investopedia.com/terms/s/smart-contracts.asp

[41] Inside Ecology: Ecological Impact of Blockchain.

https://insideecology.com/2023/04/17/ecological-impact-of-blockchain/#:~:text=Environmental%20Issues%20with%20Blockchain&text=According%20to%20a%20report%20by,the%20issue%20of%20climate%20change..

[42] Environmental Protection Agency: Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990—2021.

https://www.epa.gov/system/files/documents/2023-04/US-GHG-Inventory-2023-Main-Text.pdf

[43] Amos Wei Lun Lee, Kentaroh Toyoda, Ivan Yeow, Zhiquan Yeo, Jonathan Sze Choong Low, Wen Feng Lu. Blockchain-enabled carbon emission management system in a multi-tier supply chain, 2023.

[44] Infinity Learn: How does an Electric Torch Work?

https://infinitylearn.com/surge/physics/class-6/electricity-and-circuits/how-does-an-electric-torch-work/

[45] Sciencing: Information About Light Bulbs for Kids.

https://sciencing.com/information-light-bulbs-kids-5561995.html

[46] One Advanced, Andrew Pearson: What is batch production in manufacturing?

https://www.oneadvanced.com/news-and-opinion/what-is-batch-production-in-manufacturing/

[47] U.S. Energy Information Administration: FAQS

https://www.eia.gov/tools/faqs/faq.php?id=667&t=6.

[48] Nord-Stream: Official Web Site.

https://www.nord-stream.com/#:~:text=Nord%20Stream%20%2D%20The%20new%20gas%20supply%20route%20for%20Europe&text=Nord%20Stream's%20twin%20pipeline%20system,Europe%20through%20the%20Baltic%20Sea.

[49] Gem Wiki: Nord Stream Gas Pipeline.

https://www.gem.wiki/Nord_Stream_Gas_Pipeline#:~:text=billion%20cubic%20feet).-,Supply%20sources,Peninsula%2C%20Ob%2DTaz%20bay.

[50] Ecometrica, Matthew Brander: Greenhouse Gases, CO2, CO2e, and Carbon:What Do All These Terms Mean?

https://ecometrica.com/assets/GHGs-CO2-CO2e-and-Carbon-What-Do-These-Mean-v2.1.pdf

[51] Microsoft: A tour of the C# language.

https://learn.microsoft.com/en-us/dotnet/csharp/tour-of-csharp/

[52] Investopedia, James Chen: Transaction.

https://www.investopedia.com/terms/t/transaction.asp#:~:text=A%20transaction%20is%20a%20completed,commonly%20used%20in%20corporate%20accounting.

[53] O’REILLY: Transactions.

https://www.oreilly.com/library/view/mastering-bitcoin/9781491902639/ch05.html#:~:text=Transactions%20are%20data%20structures%20that,global%20double%2Dentry%20bookkeeping%20ledger.

[54] C# Corner: Building A Blockchain In .NET Core - Transaction and Reward.

https://www.c-sharpcorner.com/article/building-a-blockchain-in-net-core-transaction-and-reward/

[55] Educative: How do hashes work in Blockchain.

https://www.educative.io/answers/how-do-block-hashes-work-in-blockchain

[56] Microsoft: IList Interface.

https://learn.microsoft.com/en-us/dotnet/api/system.collections.ilist?view=net-7.0

[57] Oracle: Json Defined.

https://www.oracle.com/database/what-is-json/

[58] GHG Institute: Compressor Station Efficiency. Improvement GHG Project Using the Performance Standard Baseline Procedure.

https://member.ghginstitute.org/ghgcourses/Course2/downloads/NaturalGasCompressor.pdf

[59] Environmental Protection Agency: Pneumatic Controllers.

https://www.epa.gov/natural-gas-star-program/pneumatic-controllers